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THE ORIGIN OF CERTAIN CHROMITE DEPOSITS OF THE EASTERN PART OF THE BUSHVELD COMPLEX

EUGENE N. CAMERON AND MARK E. EMERSON

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ABSTRACT

Structural and lithologic characteristics of the sequence of rock units in the Critical Zone of the Bushveld Complex, on Farms Winterveld (343) and Jagdlust (333), Eastern Transvaal, are described, and the sequence of rocks including the Steelpoort and Leader chromite seams is discussed. Field observations are consistent with the concept that the layered structure of the Critical Zone is due fundamentally to gravitative accumulation of early-formed crystals, but numerous irregularities and discontinuities of layering, repetition of rock types, and cognate xenoliths indicate sedimentation from a magma that was at least intermittently in motion.

The Steelpoort seam consists of a high-grade chromitite member 44 to 48 inches thick, enclosed in two low-grade members that grade into enclosing pyroxenites. The Leader Seam consists of a high-grade chromitite member and an overlying low-grade member that grades upward into pyroxenite. Textural features of the pyroxenites and low-grade chromitite members can be accounted for satisfactorily by magmatic sedimentation of crystals of bronzite and chromite, followed by crystallization of interstitial liquid. However, textural features of the high-grade chromitite members, together with bronzite-chromite overgrowths on xenoliths and chromite veinlets in xenoliths, indicate that while the main concentration of chromite is best explained by magmatic sedimentation, chromite in the high-grade chromitite members has crystallized in part in situ.

Bronzite and chromite vary systematically in grain size and composition through the pyroxenite-chromitite sequence. From this and the textural features, it is suggested that formation of the high-grade chromitite members involved partial resolution and reaction of settled crystals with magma prior to burial, followed by reaction between settled crystals and interstitial liquid after burial. The interstitial liquid, enriched in Cr and Fe, subsequently crystallized to give bronzite, more chromite, and minor plagioclase. Downward diffusion into the interstitial liquid during crystallization may have contributed to the growth of chromite.

Formation of the chromites by accumulation of residual liquids rich in Cr and Fe is excluded by field evidence and by the paragenetic sequence of minerals in the rocks associated with the chromitites. Liquid immiscibility may have played a supplementary role in formation of the chromitites, but field and microscope evidence are against immiscibility as a principal mechanism of chromitite formation.

INTRODUCTION

THE chromite deposits of the Bushveld Complex have attracted the attention of geologists the world over since they first were reported officially by Molengraaff in 1899. The deposits are of special interest, partly because they are end members of the remarkable series of rocks composing the Bushveld Complex, partly because the chromite deposits are now known to contain a substantial share of the world's reserves of chromium ores.

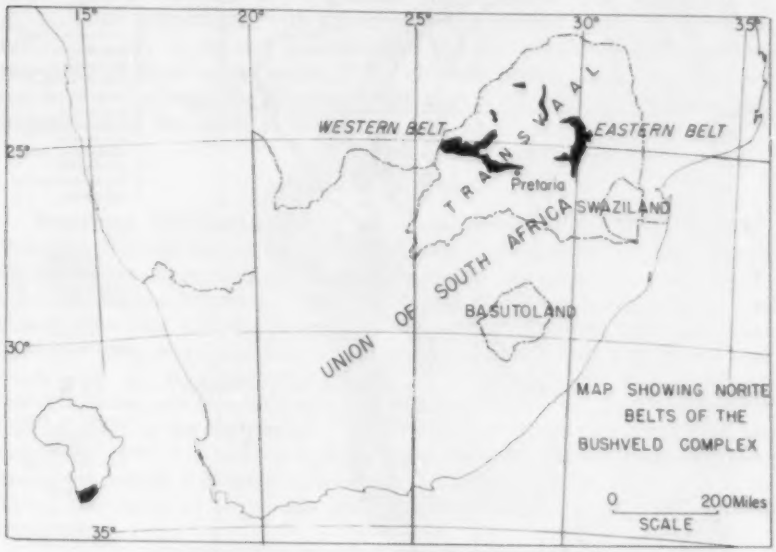

FIG. 1. Norite belts of the Bushveld Complex.

Much information has accumulated concerning the location of various deposits within the complex, the chemical varieties of chromite present in various seams, the textural relations of chromite to other minerals, and the mineral associations represented. Attempts have been made to correlate seams from part to part of the complex. Yet the deposits are so extensive and so varied in occurrence that information concerning them is far from complete. The number and extent of the seams are only partly known. The correlation of various seams from part to part of the Bushveld Complex is in many respects in doubt. The relations of variations in thickness, location, and number of chrome seams to changes in the "stratigraphy" of the Bushveld Complex along strike are not well understood. Evidence regarding the origin of the seams is conflicting, and the chromite deposits remain an enigma.

The uncertainties involved reflect the status of investigations of the Bushveld Complex. Various studies of the petrology and overall structure of the

chromitites and associated rocks have been made, but as yet only small portions of the mammoth complex have been mapped and studied in detail. For the Bushveld as a whole, information on field relations is therefore rather general in nature.

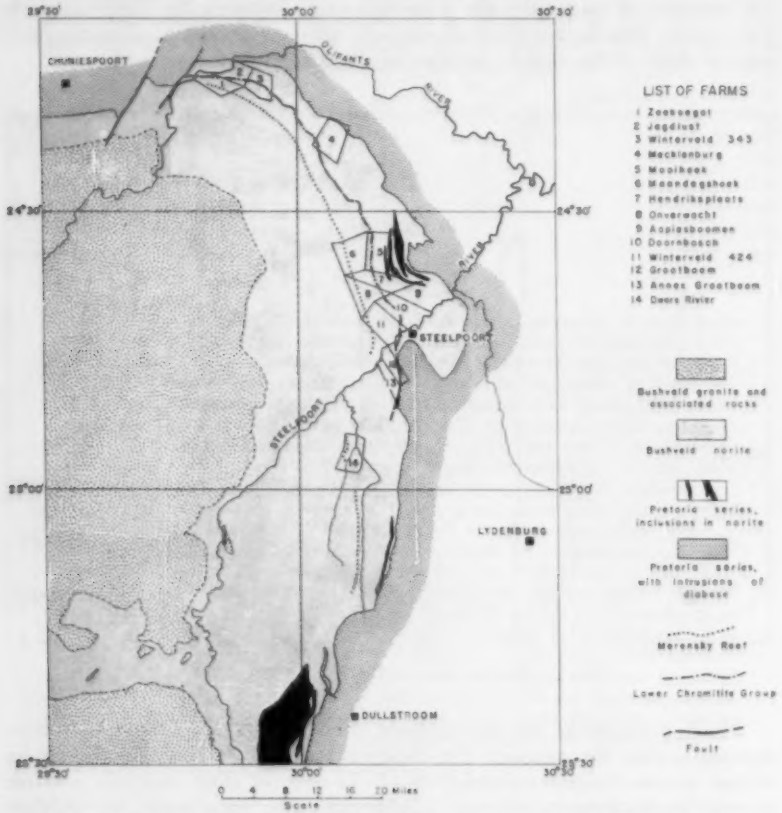

FIG. 2. Generalized geologic map of the eastern part of the Bushveld Complex, showing locations of farms mentioned in text.

During 1952–55, Cameron directed investigations of certain chromite deposits in the northern part of the eastern norite belt of the Bushveld Complex (Fig. 1), among them the deposits occurring on Farms Jagdlust (333) and Winterveld (343) * (Fig. 2). On these two farms, a thickness of about 10,000 feet of rocks in the Critical and Transition Zones of the complex was

* Note that there are two farms named Winterveld in the eastern chromite belt, Farm Winterveld (343), adjoining Jagdlust, and Farm Winterveld (424) at Steelpoort. In the present report, the first is referred to as "Winterveld," the second as "Winterveld (Steelpoort)."

mapped on a scale of 1:10,000 and studied in detail over a distance of 6 miles. Messrs. Harry E. Abendroth, David L. Welch, and Byrd L. Berman assisted in this work. Underground workings and numerous test pits in chrome seams on the two farms were examined. Surface investigations were followed in 1952–53 by diamond-drilling, and cores from the various holes were studied in the field during 1953–54. A large number of representative specimens and sections of drill core was shipped to the University of Wisconsin for laboratory study. During the period April, 1954, to May, 1955, a petrographic study of the two major chrome seams was undertaken by Emerson in consultation with Cameron. The present paper presents the results of study of the two chrome seams and the associated rocks and discusses the problem of the origin of the chromite seams. The field data are the work of Cameron, the laboratory data largely the work of Emerson. Interpretation is the work of both.

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Numerous individuals assisted the investigations. Mr. D. F. Frasché, Manager, Mineral Survey Department, Union Carbide Ore Company, was in administrative charge and encouraged the studies at every stage. Mr. O. T. van der Merwe, Director, Jagdlust Chrome Company (Pty.) Ltd., was closely associated with the program of chrome investigations, gave assistance in innumerable ways, and was a most generous host during part of the field work. Mr. H. E. Abendroth, Mr. D. L. Welch, and Mr. B. L. Berman assisted in the field investigations and were responsible for sampling and for logging some of the drill holes. To Union Carbide Ore Company, we are greatly indebted for making materials and facilities available and for permission to publish the results of the study. Professors R. M. Gates and S. A. Tyler, University of Wisconsin, have reviewed the paper and made helpful comments.

PREVIOUS INVESTIGATIONS

Many accounts of the chromite deposits and of associated rocks are given in the literature. For summaries of various investigations to 1931 the reader is referred to Hall's monumental memoir (15) on the Bushveld Complex, where they are given together with Hall's own keen observations of the rock assemblage. Certain papers, however, require special mention. Wagner (40) recognized three types of occurrence of chromite in the Bushveld Complex: (1) as minute crystals scattered through ultrabasic rocks, (2) as short, often lenticular masses mostly less than three feet in length, conformable or disconformable to the pseudostratification of the enclosing ultramafic rocks, and (3) as regular bands or lenses of chromite rock that are traceable for long distances, range up to 6 feet thick, and are concordant with the stratification of the norite. Wagner proposed the term chromitite for the last type of deposit and emphasized its close association with bronzite. Chemical data for various chromitite seams were given. Wagner concluded that the chromitites are due to gravitative concentration of early-formed crystals.

Results of petrographic studies of chromite-rich rocks were discussed by E. S. Sampson (31, 32, 33). Sampson concluded that the textural features of the chromite-rich rocks from the Bushveld are difficult to reconcile with simple gravitative accumulation of early-formed crystals and could only be explained by separate intrusions of chrome-rich magma, by crystallization of chrome-rich liquid derived by remelting of settled crystals, or by crystallization of chromite from a chrome-rich residual magma. In his last work, Wagner (41, p. 46–47) likewise rejected simple gravitative differentiation as the key to the Critical Zone of the Bushveld Complex and entertained the hypothesis of remelting of sunken crystals. At about this same time Reuning (29) suggested that the extreme members of the Bushveld are due to intrusion of special magmas produced by differentiation in depth.

Hall (15, p. 335–341) gave a summary description of the chromite-rich rocks. He concluded that formation of the chromitites was probably related in some way to gravitative accumulation, but that the exact magmatic conditions involved were probably complex.

Lombaard (24) presented a study of the petrologic significance of the differentiation and relationships of the rocks of the Bushveld Complex. He found that from the base of the Bushveld upward plagioclase in general becomes more sodic and clinopyroxene increases at the expense of orthopyroxene. In addition, orthopyroxene and chromite show progressive enrichment in iron relative to magnesia. He concluded that the Bushveld Complex is due to fractional crystallization and gravitative differentiation of successive injections of magma from a common reservoir.

Kupferberger and others (22) described the chromite deposits of the Bushveld in a report that was concerned primarily with economic aspects but contained much new information on occurrence and composition. These authors followed Hall in recognizing three groups of chromitite seams occurring in different positions below the Merensky Reef. Only the middle and lower groups were found in the eastern part of the complex. A map of the eastern part showing the distribution of seams was presented, but the authors pointed out that not all the seams recognized could be correlated satisfactorily. Studies by Cameron and Abendroth during the present investigation confirm this. The tentative correlations by Kupferberger and Lombaard seem to hold reasonably well for the section between the Steelpoort River and Farm Jagdlust. South of this sector, however, the stratigraphic section of the lower part of the Bushveld and the succession of chrome seams are markedly different. Scattered observations by Cameron suggest that marked changes may also occur northwest and west of Farms Zeekoegat and Jagdlust, beyond the limits of Figure 2.

Kuschke (23) showed that in the Eastern Transvaal orthopyroxene associated with chromitite is commonly richer in MgO than orthopyroxene in accompanying pyroxenites. Van der Walt (37) showed that in the Western Transvaal chromite and pyroxene in a given chromitite seam differ in composition from the same minerals in closely associated pyroxenites.

De Wet (8) published the results of chemical analyses of Transvaal chromite. He demonstrated that chromite from the Steelpoort Main Seam is

surprisingly uniform in composition for tens of miles along strike as well as across the width of the seam. De Wet and Van Niekerk (9) presented X-ray data for chromites from various seams of the Bushveld Complex. Fockema and Mendelssohn (13) discussed the characteristics of one of the chromite seams below the Steelpoort Seam on Farm Aapiesboomen. Emerson (11) described the petrography of the Steelpoort and Leader seams and discussed the problem of origin.

THE EASTERN PART OF THE BUSHVELD COMPLEX

General Description.—The noritic assemblage of the Bushveld has been described by many authors and its general characteristics need only brief review. The norites and associated ultrabasic rocks of the eastern part of the Bushveld Complex were divided by Hall into five successive zones, which are summarized in Figure 3. The five zones are best displayed in parts of

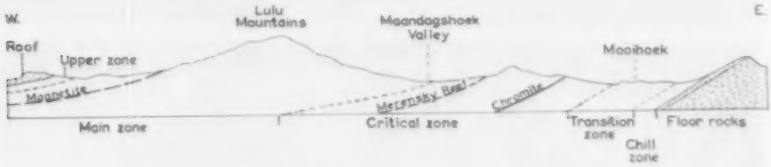


FIG. 3. Section of the Bushveld norite north of Steelpoort, after A. L. Hall, showing the major zones from floor to roof. Length of section 19 miles.

the section between Farm Jagdlust on the north (Fig. 2) and the Steelpoort River on the south. The Transition and Critical zones attain their finest development on Farm Jagdlust and adjacent Farm Winterveld. Northwest of Jagdlust and Zeekoegat exposures are poor. South of the Steelpoort River the five zones are not everywhere distinct, and much remains to be done to decipher the "stratigraphy" of the Bushveld in this direction.

So far as known, chrome-rich rocks in the Eastern Transvaal are restricted to the "Critical Zone" of Hall's section, although Hall pointed out (15, p. 309, 335) that chromite occurs as an accessory mineral in the Transition and Chill Zones. The Critical Zone in the Eastern Transvaal is renowned for its pseudostratified structure (Fig. 4). It is a pile of layers, fractions of an inch to many feet in thickness, of bronzitite, norite, anorthosite and chromitite, with types representing every gradation in between. In general these rocks dip to the west or southwest at angles ranging from 10 to 45 degrees, but south of the Steelpoort River the structure is complicated by folding and faulting of the rocks beneath the Main Norite Zone.

THE CRITICAL ZONE ON FARMS JAGDLUST AND WINTERVELD

General Description.—The rocks studied on Farms Jagdlust and Winterveld belong to the lower and middle part of Hall's Critical Zone. The "stratigraphic" succession is shown in Figure 6, and the distribution of the various

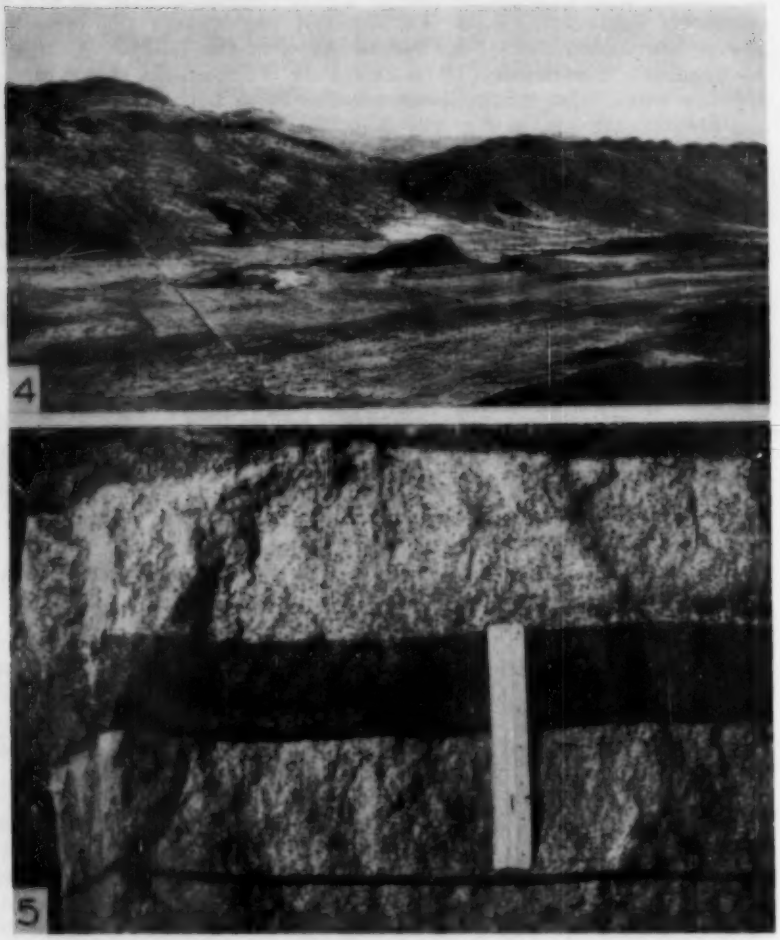


FIG. 4. View of Farm Jagdlust, looking southwest from Rostock Hills. Low ridges in foreground and middle ground are formed on pyroxenites of the Transition Zone, high ridge beyond on units of the Critical Zone. Jagdlust mine is just to the right of the deep reentrant in the ridge. To right of reentrant, ridge is capped by anorthosites of M unit; to left of reentrant, high knob is formed on anorthosites of X unit. Thin line nearly halfway down ridge is outcrop of massive pyroxenite forming lower part of L unit.

FIG. 5. Layers of chromiferous pyroxenite in anorthosite near top of M unit near east end Farm Winterveld. Scale is 6½ inches long.

major units recognized is shown in Figure 7. The lower half of the section is composed largely of pyroxenites and mafic norites, whereas the upper half consists largely of anorthosite and norite. The units shown on the map are remarkably persistent, with the possible exception of units O and W. The

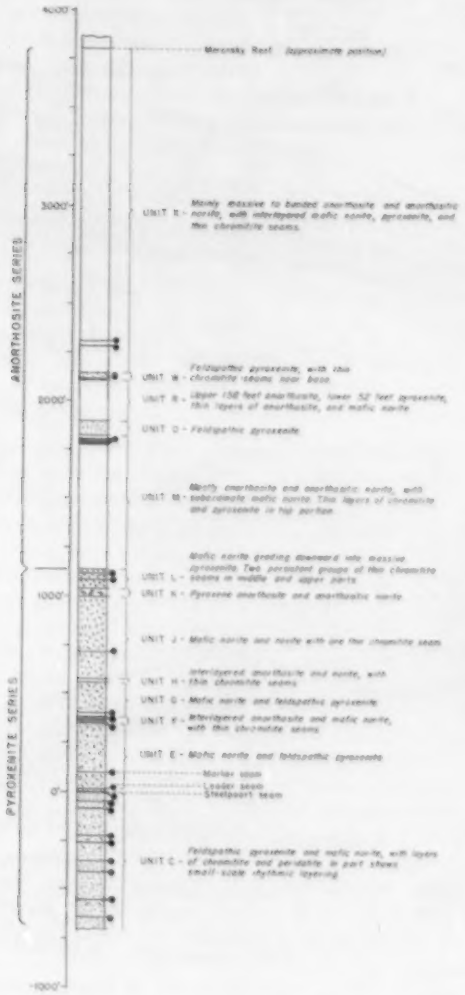


FIG. 6. Sequence of major units in the Critical Zone on Farms Jagdlust and Winterveld (343), Lydenburg District, Transvaal. Large black circles to right of column mark chromitite seams.

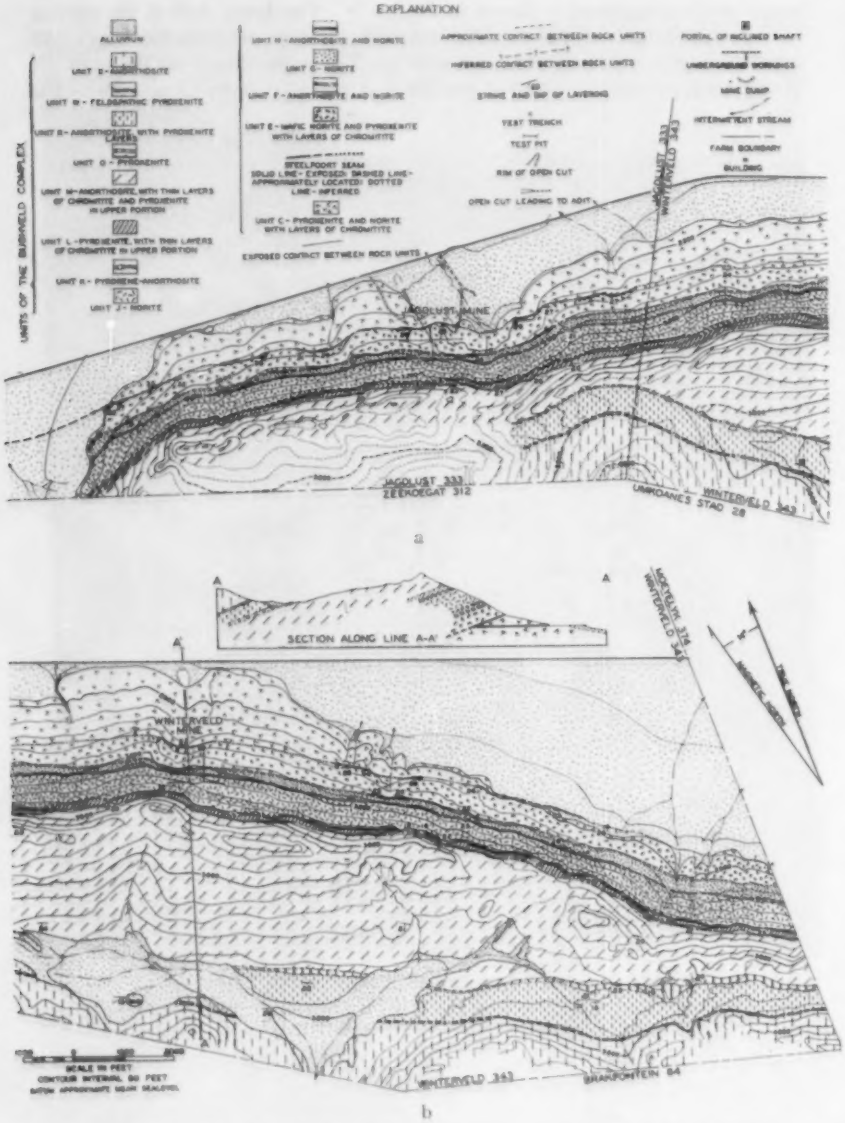

EXPLANATION
ALLUVIUM
UNIT B - ANORTHOSITE
UNIT M - FELDSPATHIC PYROXENITE
UNIT B - ANORTHOSITE WITH PYROXENITE CAPS
UNIT O - PYROXENITE
UNIT M - ANORTHOSITE WITH THIN LAYERS OF CHROMITITE AND PYROXENITE IN UPPER PORTION
UNIT L - PYROXENITE WITH THIN LAYERS OF CHROMITITE IN UPPER PORTION
UNIT A - PYROXENE-ANORTHOSITE
UNIT J - NORITE
UNITS OF THE BUSHVELD COMPLEX
UNIT H - ANORTHOSITE AND NORITE
UNIT G - NORITE
UNIT F - ANORTHOSITE AND NORITE
UNIT E - MAFIC NORITE AND PYROXENITE WITH LAYERS OF CHROMITITE
STEELPOORT SEAM SOLID LINE - EXPOSED; DASHED LINE - APPROXIMATELY LOCATED; DOTTED LINE - INFERRED
UNIT C - PYROXENITE AND NORITE WITH LAYERS OF CHROMITITE
EXPOSED CONTACT BETWEEN ROCK UNITS
APPROXIMATE CONTACT BETWEEN ROCK UNITS
INFERRED CONTACT BETWEEN ROCK UNITS
STRIKE AND DIP OF LAYERING
TEST TRENCH
TEST PIT
RIM OF OPEN CUT
OPEN CUT LEADING TO ADIT
PORTAL OF INCLINED SHAFT
UNDERGROUND WORKINGS
MINE DUMP
INTERMITTENT STREAM
FARM BOUNDARY
BUILDING
JAGDLUST MINE
JAGDLUST 333
ZEEKOEGAT 312
WINTERVELD 343
UMPOANES STAD 28
a
A
A'
SECTION ALONG LINE A-A'
WINTERVELD MINE
WINTERVELD 343
BRANDFONTEIN 84
b

FIG. 7. Geologic map of the southern portions of Farms Jagdlust (333) and Winterveld (343), Lydenburg District, Transvaal, based on plane-table surveys by E. N. Cameron, H. E. Abendroth, D. L. Welch, and B. L. Berman, 1952–55.

broad valley along the south central boundary of Farm Winterveld interrupts exposures of these two units, and their extensions across the western part of Farm Jagdlust have not been traced. The other units are so well exposed or indicated by drilling that their continuity is not in doubt. Each of these units, however, is composed of a sequence of thinner units. Some of these individual units are lenses a foot or less in length, whereas others are traceable for the full six miles of strike included within the limits of the two farms. Sections measured by H. E. Abendroth (personal communication) across the same parts of the Critical Zone on Farms Mecklenburg, Hendriksplaats, and Doornbosch have a general resemblance to the section given, and the component units make up broadly similar sequences. The sequences, however, are not identical.

Lithologic and Structural Features.—Certain lithologic and structural features of the Critical Zone observed in the field are especially pertinent to the problem of the origin of chromite. These are the following:

1. Gradations between rock types.
2. Pseudostratification.
3. Indications of deformation.
4. Persistence of individual units.
5. Inclusions of one rock type in another.
6. Replacement phenomena.

Gradations Between Rock Types.—The various rock types of the section of the Critical Zone here discussed can be considered as members of a ternary series having pyroxenite, anorthosite and chromitite as end members. The pure end members are apparently nowhere represented, although certain layers in the sequence very closely approach one end member or another. A rich variety of intermediate members, however, is represented. Field study suggests that every gradation between nearly pure anorthosite and nearly pure pyroxenite, through norite, is represented, and gradations of all these rocks to nearly pure chromite rocks are found.

Pseudostratification in the Critical Zone.—Previous investigators have shown that the structures of the Critical Zone included under the name of pseudostratification are a varied assemblage. This assemblage is well represented in the section studied. At one extreme are layers that have contacts that are straight and parallel for feet, tens of feet, or even hundreds of feet (Fig. 8). This type of layering is shown, in the part of the Critical Zone studied, by most of the pyroxenites, mafic norites, and chrome-rich rocks. Layering is due to changes in texture or mineral proportions, or both. Contacts are commonly abrupt transitions, but some are of knife-edge sharpness (Fig. 5; Fig. 9). The layers range from fractions of an inch to many feet in thickness. Rapid alternations of inch to 6-inch layers are especially characteristic of the portion of the Critical Zone beneath the Steelpoort Main Seam (Fig. 8). Chromite seams in the pyroxenites of the Critical Zone characteristically are evenly and regularly layered, and on the whole, even, regular layering is the commonest type of pseudostratification in the section of the Critical Zone studied.

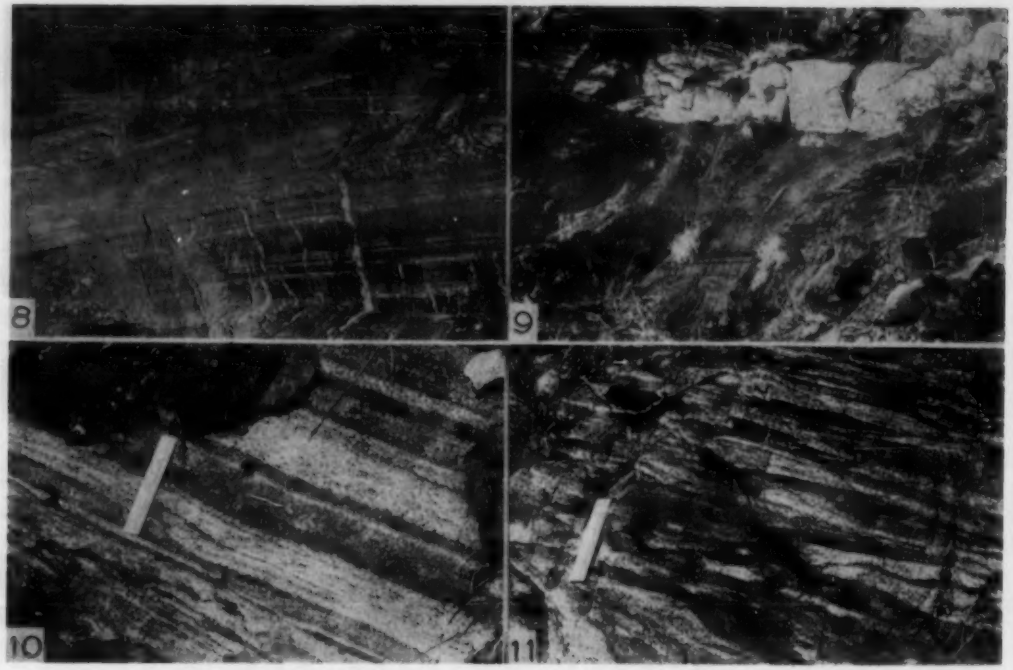


FIG. 8. Regular layering in pyroxenites of C unit in entrance to main adit, Winterveld mine. Layers are a fraction of an inch to 6 inches thick.

FIG. 9. Contact between anorthosite (white) of F unit and mafic norite of E unit (gray, below) above Jagdlust mine. Note thin layers of chromitite in E unit beneath hammer.

FIG. 10. Interlayered norite and pyroxene-bearing anorthosite of K unit above Jagdlust mine. Note contrast between even layering above and layering below. Scale is 6½ inches long.

FIG. 11. Lenticular structure in anorthositic norite of K unit above Jagdlust mine. Compare with Fig. 10 above. Scale is 6½ inches long.

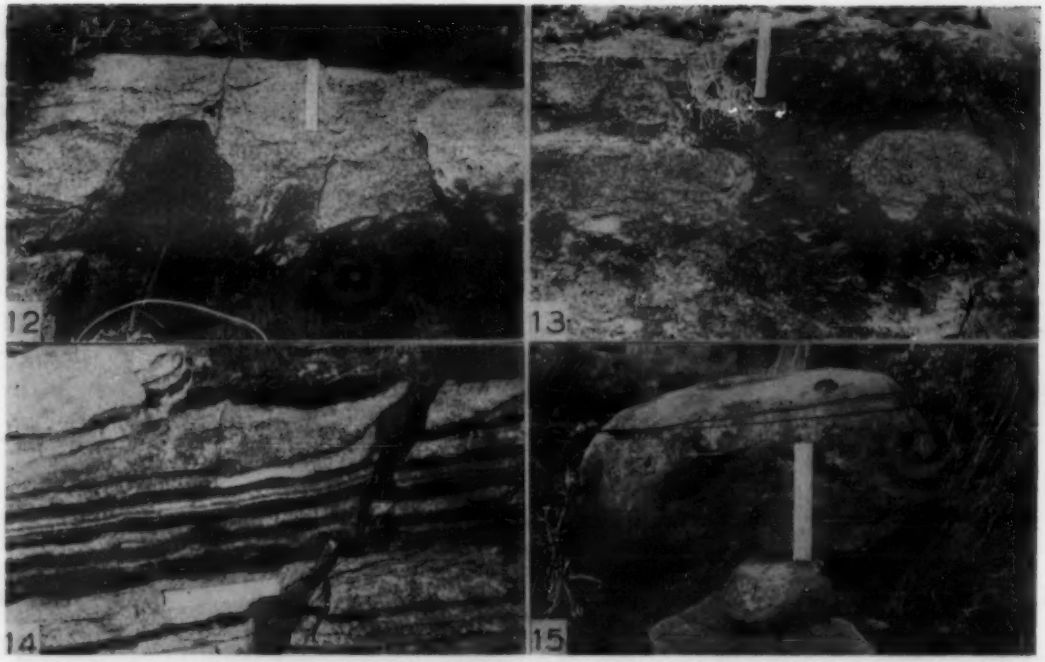


FIG. 12. Anorthosite layer (white) at base of H unit, Farm Winterveld, showing relief of contact with underlying mafic norite of G unit. Scale is 6½ inches long.

FIG. 13. Norite layer (below hammer to left and right) interrupted by pyroxenite, E unit, Farm Winterveld. At left and right norite is underlain and overlain by pyroxenite; in center norite is interrupted by pyroxenite. Lichens obscure contacts at left.

FIG. 14. Layer of anorthosite (light gray) interrupted by chromitite (black), in M unit, west edge Farm Moeyelyk. Scale is 6½ inches long.

FIG. 15. Intersecting fracture fillings of chromitite and anorthosite, in loose block from upper part of M unit, east end Farm Winterveld. Scale is 6½ inches long.

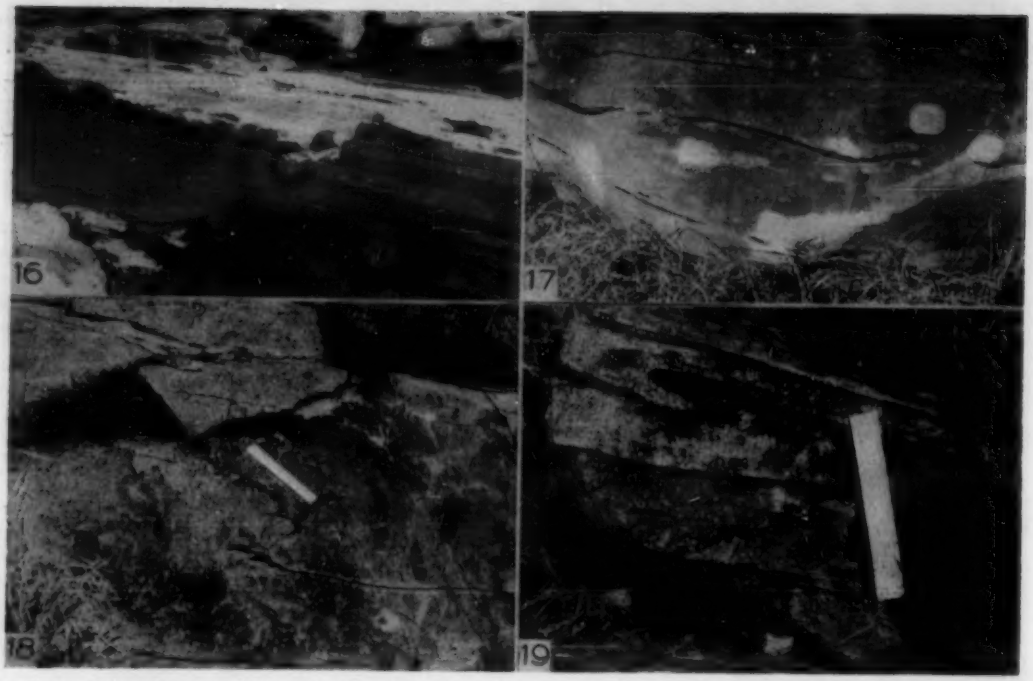


FIG. 16. Intersecting fracture fillings of chromitite (black) in anorthosite (gray), Dwars Rivier.
FIG. 17. Fragmented thin chromitite seams (black) in anorthosite (gray), upper part of M unit, east end, Farm Winterveld.
FIG. 18. Deformed thin chromitite seam (black, below 6½-inch scale), upper part of M unit, Farm Winterveld.
FIG. 19. Folded pyroxenite layer (dark gray) in pyroxene anorthosite (lighter gray), loose block, upper part of M unit, east end Farm Winterveld. Note that the upper and lower pyroxenite seams are undeformed. Scale is 6½ inches long.

A quite different type of layering is shown in the anorthositic norite of unit K. This unit commonly consists of intricately intercalated lenses of pyroxene-bearing anorthosite and norite fractions of an inch to three or four inches thick and a few inches to a few tens of feet long (Fig. 11). Such rock was called banded anorthosite by Hall. The total structure is what one might expect if a pile of alternating, still incompletely consolidated layers of anorthosite and norite had undergone movement sufficient to dismember and jumble the layers to some extent but insufficient to produce complete mixing of the two. The degree of disturbance of the original layered structure varies, and locally a regular layering is preserved (Fig. 10). In this connection, it should be noted that the contact of the unit with the underlying norite is sharp and uneven, like certain contacts described below.

Less common than the above are layers that are persistent over long distances but have very uneven contacts with adjacent units. These contacts resemble disconformities in ordinary sedimentary rocks. The most striking examples are the lower contacts of certain anorthosite layers that are underlain by norite. The contacts are knife-sharp and range from even to decidedly uneven. The contacts may show several feet of relief within a few tens of feet, and locally troughs and pinnacles in contacts are found. One example, from unit H, is shown by Figure 12. Along the base of the anorthosite layer there is a thin but persistent chromite concentration. Note that the upper contact of the anorthosite is even and regular.

In unit H on Jagdlust, the lower contact of an associated impure chromitite seam is similarly uneven. The basal portion contains inclusions of the underlying chromite-bearing anorthosite. Contacts of this type appear to be akin to those described from the Merensky Reef by Schmidt (35), who presents strong evidence that they are due to erosion by magmatic currents.

Another type of structure is illustrated by Figure 13, and Figure 14. In the first figure pyroxenite enclosing a layer of norite breaks abruptly across the norite. In the second, chromite interrupts a layer of anorthosite.

Indications of Deformation.—Structures indicating deformation are remarkably well displayed in the upper part of the M anorthosite unit. Numerous outcrops near the east end of the map area show pyroxenite and impure chromitites apparently interbanded with anorthosite. Closer inspection shows, however, that in many cases the "layers" of pyroxenite and chromitite intersect at low angles, and in places they are clearly fracture fillings in anorthosite (Fig. 15), not lenses or cross-laminations. Such seams are structurally identical with the well known chromite-rich fracture fillings at Dwars Rivier (Fig. 16), described by Hall (15), Sampson (31), Bateman (2), and others. The chromitites and pyroxenites of the M unit on Winterveld are therefore controlled at least in part by deformation of the anorthosite, but they themselves have been deformed. Locally they are thrown into systems of minor folds or even completely dismembered, so that detached fragments of chromitite or pyroxenite appear "frozen" in anorthosite (Figs. 17, 18, 19). It should be noted that precisely similar deformation and dismemberment of chromite seams is shown at the upper end of the gorge at Dwars Rivier (Figs. 20, 21).

Two features of the occurrences in the M unit on Farm Winterveld, taken together, suggest penecontemporaneous deformation. One is that deformation is highly localized "stratigraphically." The thickness of rocks involved is commonly only a few feet, and overlying rocks are undeformed. The second is that even where chromite and pyroxenite seams have been dismembered, the enclosing anorthosite shows no signs of deformation. Breaks in the dismembered seams appear healed by anorthosite in no wise differing from the anorthosite between the layers. This feature argues for development of the structure when the anorthosite was a mush of crystals with interstitial liquid. In the early stages of deformation the anorthosite fractured, but under later stress it flowed.

Persistence of Individual Units.—From what has been said above, it will be evident that the layers and pseudo-layers of the Critical Zone exhibit a wide range of lateral persistence in the area studied. For obvious reasons, the lower limits of lateral persistence are simpler to establish than the upper limits. The upper limits can be determined only for exceptionally distinctive, well-exposed individual layers. Certain chromitite seams meet this requirement, notably the Steelpoort Main Seam, the Leader Seam and the Marker Seam, which is 90 to 100 feet above the Leader Seam. Outcrops, test pits, mine workings, and drill holes indicate beyond doubt that these seams extend from one end of the area of Figure 7 to the other, a distance of more than 6 miles, without interruptions save those due to minor post-Bushveld faults and diabase dikes. Furthermore, the Steelpoort and Leader Seams are found from Jagdlust to the Steelpoort River at all places where the rocks of the appropriate horizons are exposed in outcrops or have been exposed in test pits and trenches, drill holes, and mine workings. The original continuity of the two seams over a strike length of roughly 40 miles can scarcely be questioned.

The Marker Seam is currently of no economic interest, and its persistence beyond the area of Figure 7 has not been determined. It is worth noting, however, that a similar seam has been found at essentially the same stratigraphic position on Farms Hendriksplaats, Onverwacht, Doornbosch, and Winterveld (Steelpoort).

Inclusions in Rocks of the Critical Zone.—Scattered inclusions of one rock type in another are a characteristic feature of the parts of the Critical Zone studied. The following associations have been noted: chromitite inclusions in norite, pyroxenite, anorthositic chromitite, and anorthosite; pyroxenite inclusions in chromitite; norite inclusions in chromitite; anorthosite inclusions in chromitite; mafic norite inclusions in anorthosite; gneissic anorthosite inclusions in massive anorthosite, and anorthosite inclusions in norite. Inclusions of pyroxenite in norite and of norite in pyroxenite have not been noted, but might well be disclosed by a special search.

The inclusions vary in characteristics. Some have angular outlines and knife-sharp contacts; others have rounded ends and boundary features suggesting reaction rims; still others have "fading" contacts. In a few places, inclusions can be seen to have developed by deformation and dismemberment of layers and lenses of one type in another. In other cases, the inclusions

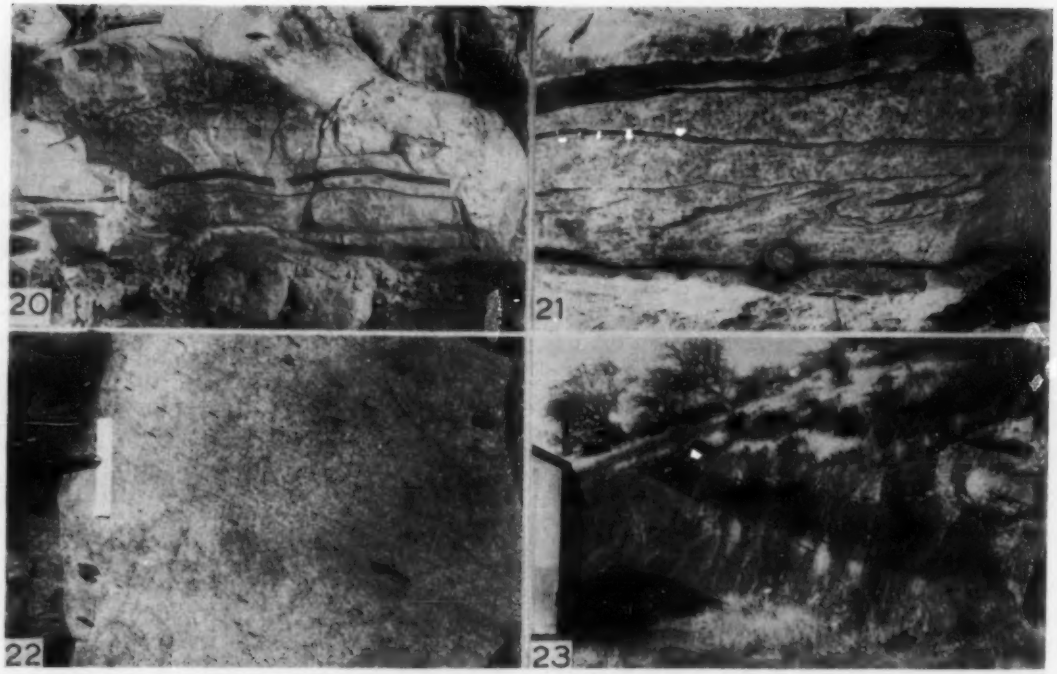


FIG. 20. Dismembered chromitite seams in anorthosite (white) at Dwars Rivier. Note scattered blocks of chromitite in upper part of exposure.

FIG. 21. Deformed layers of chromitite (black) in anorthosite, Dwars Rivier.

FIG. 22. Inclusions of chromitite (black) in gneissic anorthosite, upper member of F unit, Farm Winterveld. Scale is 6½ inches long.

FIG. 23. Steelpoort Seam (thick black layer) and Leader Seam (thinner black layer above at right) exposed in open cut at Jagdlust mine. Lower member of Steelpoort Seam shows as dark gray band below thicker black middle member. Upper member of seam is marked by rubbly band.

occur very widely scattered with no indication of source or mechanism of derivation. In general, the inclusions are tabular or lenticular, and have their long dimensions parallel to the pseudo-stratification of the host rock. Most are small, 6 inches or less in length and 2 inches or less in thickness (Fig. 22).

The occurrence of inclusions through the stratigraphic succession is not uniform. They are most conspicuously developed and most numerous at four horizons in the sequence of Figure 6; namely, in the Steelpoort Main chromite seam, in and associated with unit F, in and associated with unit H, and in the upper part of unit M. In particular, inclusions are abundant where chromitite, anorthosite, and norite or pyroxenite are closely associated. It would seem that such associations are genetically related in some manner to times of disturbance.

Replacement Phenomena.—Patches, streaks, and fracture-controlled vein-like bodies of pure plagioclase occur at many places in the norites of unit J. Their boundaries cut irregularly across the pseudostratification, and they have evidently formed by feldspathization of pyroxene-bearing rocks. The bodies are mostly small, a few feet or less in length and a few inches or less in thickness. The effects are decidedly local, and indications that the bodies are related to through-going channels are never seen. They seem best interpreted as penecontemporaneous with the enclosing rock.

A somewhat different set of phenomena is illustrated in many places in units F and H. These two groups of units are persistent across the entire length of the two farms, but are extremely varied internally. The component anorthosites, impure chromitites, and norites have complex relations to one another. Interpenetration of chromitite and anorthosite, or chromitite and norite, and of anorthosite and norite are repeatedly shown. In general the relations suggest fracturing of one type of rock and invasion by a second, with irregular replacement or assimilation of the original rock. There is no fixed sequence. Anorthosite invades chromitite, and vice versa, and both invade norite. In general where two rocks are in interpenetrating contact, the lower one appears to have been invaded. Each type of rock contains scattered inclusions of the other types. Relations in these two units at any one spot could easily be interpreted as evidence of metasomatic replacement subsequent to consolidation, but when the lateral persistence of the assemblages as a whole and of certain units within them are considered, the hypothesis becomes unattractive. A more reasonable explanation is that the formation of these assemblages was attended by periodic structural disturbance or movements in magma, by which layers already consolidated were at times partly eroded, at times fractured and exposed to reaction with whatever liquids were available. Only in this way does it seem possible to explain (1) inclusions of each rock type occurring in all other rock types, (2) the disconformable, apparently erosional contacts between units described previously, and (3) the lack of a consistent sequence in the development of rock types. Further study of this horizon is needed.

Metasomatic replacement clearly subsequent to consolidation of the rocks of the Critical Zone is not at all uncommon in the eastern part of the Bushveld.

On Hendriksplaats, Mooihoek, Maandaagshoek, Grootboom, and Annex Grootboom farms, replacement of anorthosite, pyroxenite, norite, and even chromitite by coarse granitoid to pegmatitic material is shown in many places. The material is composed essentially of plagioclase and clinopyroxene in various proportions, but locally hornblende, biotite, ilmenite, and other minerals are present. Bodies of such material have outlines that transgress the pseudostratification of the Critical Zone and were clearly developed after the pseudostratification. The patterns are in marked contrast to those discussed above.

CHROMITITES ASSOCIATED WITH PYROXENITES AND MAFIC NORITES IN THE LOWER PART OF THE CRITICAL ZONE

General Remarks

The principal chrome-rich layers recognized in the lower part of the section of the Critical Zone studied are shown in Figure 6. Other chrome-rich layers are known to exist in still lower parts of the section, but these are poorly exposed on Jagdlust and Winterveld farms and have not been studied in detail. The principal chromitite layers are the Steelpoort Main Seam, the Leader Seam, and the Marker Seam, all members of the Lower Group of chromitite seams (5). Of these only the Steelpoort Main Seam and Leader have been studied in detail as yet, and the discussion below is devoted principally to these. Their appearance in clean exposures is illustrated in Figure 23.

Steelpoort Main Seam

General Description.—The Steelpoort Main Seam is extensively exposed on Jagdlust and Winterveld farms, and is remarkably constant in megascopic features. It consists of three members (Figs. 23, 24). The middle member, 44 to 48 inches thick, consists of chromite with small amounts of silicates, mostly bronzite and plagioclase. In weathered outcrops or exposures, the middle member shows greenish spots which are due to scattered highly poikilitic bronzite crystals $\frac{1}{8}$ to $\frac{3}{8}$ inch across. Assays of 42 channel samples of this member from mine workings, drill cores, and surface pits and exposures show the following:

Cr_2O_3	43.00%	to	47.30%
FeO	23.45	to	26.11
SiO_2	0.56	to	4.80
Al_2O_3	13.75	to	17.15
MgO	10.25	to	11.45
CaO	0.10	to	2.39
TiO_2 (8 samples only)	0.45	to	0.46

Each sample covered the full width of the middle member of the seam, including partings and inclusions where present. The wide range of values given is explained partly by this, partly by variations in content of disseminated pyroxene and plagioclase, and to a minor extent by variations in the composition of chromite.

FIG. 24. Steelpoort Seam and underlying pyroxenite. The man's finger is on the transitional contact of the middle member and the lower member, base of which is at his elbow.

FIG. 25. Photomicrograph of chromite-bearing pyroxenite above Leader Seam, showing chromite (black) interstitial to bronzite (higher relief, gray) and forming rudimentary second-order network with interstices occupied by plagioclase (twinned, lower relief). Nicols, × 26.

Underneath the middle member is the lower member, which averages about 16 inches in thickness. Its contact with the middle member is marked by an abrupt downward increase in the content of pyroxene. Pyroxene in the lower member forms rounded crystals having their long dimensions parallel to the contact. The ratio of chromite to silicates decreases steadily downward in the lower member, and the member passes gradationally into the underlying pyroxenite, which contains only accessory chromite. The boundary between the lower member and the pyroxenite is taken somewhat arbitrarily as the point at which an increase in chromite over the average of the pyroxenite is detected megascopically.

The upper member is similar to the lower member and has the same relations to the middle member and overlying pyroxenite as those described for the lower member. Its base is marked by a distinct increase in the ratio of silicates to chromite. Upward the upper member passes gradationally into pyroxenite with accessory chromite.

The chromitite of the middle member is ordinarily quite friable, disintegrating rapidly into a black sand when exposed to weathering, or during mining and handling. Locally, however, the seam is crossed by shear zones that are marked by parallel fractures or faults of small displacement. Chromitite associated with these shear zones is commonly extremely hard. In the main level at the Winterveld mine the main chromitite seam is transected obliquely by a set of such shears over a strike length of 360 feet.

Scattered through the middle member of the Steelpoort Main Seam are numerous inclusions of brown to greenish bronzitite. The great majority are composed of fine-grained bronzitite, but some are layered and are composed partly of fine-grained bronzitite, partly of coarser feldspathic bronzitite. A small minority consist of coarse bronzitite. Accessory clinopyroxene is present in some inclusions. Inclusions observed range from less than an inch long and fractions of an inch thick to 52 inches long and 6 inches thick. The inclusions are tabular and are invariably oriented with their two longer axes parallel to the contacts of the middle member. All are straight, regardless of thickness. One perfectly straight inclusion in the middle member in the Jagdlust main level is 21 inches long and only half an inch thick. Some inclusions taper out gradually at their ends, but most are bluntly rounded or taper abruptly. Contacts of some inclusions are knife-sharp, but most appear marked by selvages of pyroxene and chromite that are commonly $\frac{1}{32}$ inch to $\frac{1}{8}$ inch in thickness.

Most of the inclusions are massive, but a small percentage show veining by chromite. The veins cut across the inclusions at various angles. All veins seen are less than $\frac{1}{2}$ inch thick. Most are simple veins, but a few are branching.

In addition to the inclusions, most of which are a few feet or less in length, there are interruptions of the chrome seam that are of relatively great lateral extent and appear to be partings rather than inclusions. They are best displayed in the main level of the Winterveld mine, east of the main incline. They vary in thickness from fractions of an inch to 5 inches thick. Near the base of the middle member one sequence of 2 to 4 partings $\frac{1}{4}$ inch to $\frac{1}{2}$ inch

thick (two partings wedge out along strike) is exposed for 100 feet. Another pair near the top of the seam consists of a lower parting ¼ inch to 2 inches thick separated by ½ inch of chromitite from an upper parting ¼ inch to 5 inches thick. The members of the pair are continuous for 175 feet. The upper parting thickens westward as the lower parting thins.

Unlike the inclusions, the partings show no pyroxene-chromite selvages. The partings have contacts with enclosing chromitite that range from abrupt to gradational, like those of the chromitite seams with the enclosing pyroxenites. No evidence of a genetic relation between partings and inclusions has been seen. It is possible, however, that the inclusions are derived from partings dismembered by movements during formation of the seam, and that the veinlets of chromite in the inclusions fill fractures produced at the same time. One would expect to see a display of the various stages of this process, but the lack of it in the present exposures is not proof one way or another.

Inclusions are less common in the upper and lower members of the seam but occur in places.

Pyroxenite Underlying the Steelpoort Main Seam.—The pyroxenite underlying the Steelpoort Main Seam is a massive, medium-grained bronzitite with minor plagioclase and accessory chromite disseminated in small grains and clusters of grains.

Pyroxenite Overlying the Steelpoort Main Seam.—This rock in general is similar to that underlying the Steelpoort Main Seam. It ranges from 3½ to 4 feet in thickness. At one place in the main level at the Jagdlust Mine, a slab of chromitite 8 inches long and ⅜ inch in thickness is included in the pyroxenite. The upper surface of the slab is 1½ inches below the base of the Leader chromitite seam. There is nothing to suggest that the enclosure is derived from an adjacent part of the chromitite seam.

The Leader Seam

The Leader Seam consists of two members, a lower member 11 to 12 inches thick consisting of massive chromitite, and an upper member 1 to 2 inches thick. The upper member is similar to the upper member of the Steelpoort Main Seam. In general, it has similar relations to the underlying massive member, except that an ⅛-inch to 1-inch pyroxenite parting separates it from the massive member in places. Its chromite content decreases upward until it passes into pyroxenite containing only accessory chromite. The contact of the lower member with underlying pyroxenite varies from abrupt to a rapid gradation over a thickness of ½ inch. In places the Leader Seam is interrupted by a 1-inch parting of chromite-bearing pyroxenite 2 inches below its top. Like the Steelpoort Main Seam, the Leader Seam contains inclusions of pyroxenite.

SUMMARY OF SIGNIFICANT FEATURES OF THE STEELPOORT AND LEADER SEAMS AS SEEN IN THE FIELD

The following appear to be the significant features of the Steelpoort and Leader chromitite seams as observed in the field:

1. Both seams are enclosed in feldspar-bearing bronzitite containing accessory chromite.

2 Each seam includes a member consisting of nearly pure chromitite (apart from inclusions and partings).

3. The middle, purer member of the Steelpoort Main Seam is enclosed in zones of impure chromitite that grade into the pyroxenite above and below the seam.

4. The Leader Seam has two members: a lower, purer member in sharp or gradational contact with underlying pyroxenite, and an upper, impure member grading upward into pyroxenite.

5. Both seams contain inclusions and partings of pyroxenite.

6. Some of the inclusions in the Steelpoort Seam are veined by chromite.

7. The inclusions do not appear to have been derived from the immediately adjacent pyroxenites.

8. The inclusions commonly have rounded ends suggesting modification by reaction. Pyroxene-chromite selvages are present around many inclusions.

9. Inclusions of chromitite occur in the enclosing pyroxenites.

10. Aside from variation in number and size of inclusions and partings, the seams are constant in lithology over a distance of 6 miles along strike.

11. The Steelpoort and Leader Seams are essentially parallel for 6 miles on Farms Winterveld and Jagdlust and are consistently separated by about 3½ to 4 feet of pyroxenite.

INTERPRETATION OF THE FIELD RELATIONS OF THE CHROMITITE SEAMS AND ASSOCIATED ROCKS

The field evidence cited above can be used for a first evaluation of various explanations of the rocks of the Critical Zone. Four principal hypotheses of origin have been proposed:

1. The chromitite seams are due to selective replacement of certain layers in an original assemblage of sediments.

2. The chromitite seams are magmatic in origin but represent successive injections of chrome-rich magma.

3. The chromitite seams are magmatic in origin and are due to fractional crystallization and gravitative accumulation of successive crops of crystals.

4. The chromitite seams represent chrome-rich liquids derived
   (a) As end-stage liquids of magma that crystallized *in situ*, or
   (b) By separation and settling of an immiscible chrome-rich liquid, or
   (c) By resorption of settled crystals of chromite.

Any of these hypotheses that satisfactorily accounts for the features of the seams themselves must also stand scrutiny in the light of the features of the associated rocks of the Critical Zone.

The first hypothesis is an extension of the theories of granitization to the development of the layered complex of the Bushveld. According to Wagner (41), this was first suggested by E. Kaiser. More recently, van Biljon (3) has argued that north of Pretoria the sediments of the upper

part of the Pretoria series pass along strike into the norite complex. Van Biljon's conclusions for the western part of the Bushveld must be evaluated by those who are familiar with the area he studied. The present writers can only examine the hypothesis in the light of features observed in the eastern part of the Complex during the present investigation.

If van Biljon's hypothesis is applicable to the eastern part of the Complex, the Steelpoort Main Seam and Leader Seam are certain sedimentary beds that have been selectively replaced by chromite before or after conversion of these beds to pyroxenites. We may suppose that the bed replaced by the Leader Seam originally was in gradational contact with an overlying bed now converted to pyroxenite but was in rather sharp contact with an underlying bed. We must then suppose that the layer now converted to the Steelpoort Seam had mineralogically gradational contacts, both above and below, with beds now pyroxenite. Inclusions and partings in the chromitite seams must be viewed as remnants of the layers replaced. Now the great majority of the inclusions, both those in the chrome-rich members and in the low-grade zones, are pyroxenites, like the rocks enclosing the chromitites. We therefore cannot call on selective replacement controlled by contrasts in composition of original sediments. We must suppose instead that selective replacement was controlled by contrasts in permeability or texture. We must suppose that this control was so perfect that over a distance of six miles along strike, considering only the exposures on Winterveld and Jagdlust farms, the chrome-rich members of the two seams developed with only a narrow range of composition and thickness.

Despite abundant evidence of the selective powers of metasomatism in the literature of economic geology and petrology, one may well hesitate before subscribing to a hypothesis that requires such perfection on such a far-flung scale. The Bushveld itself, however, is a phenomenon without parallel in scale; hence objections would perhaps arise from the limitations of human experience. A careful search of exposures, particularly those in the mine workings, has therefore been made to determine whether the inclusions and partings are remnants of a replaced layer or group of layers, but the result is evidence to the contrary. At a few places tabular inclusions with their sides parallel to the top and bottom of the Steelpoort Seam are found in line with one another. If two tabular inclusions are in line and represent remnants of a replaced layer, they should be the same in lithology unless they have been affected by the chromitite, have been differently altered since formation of the chromitite, or have been displaced by later movement. Inclusions in line with one another in the Steelpoort Seam are not always the same. At one place in the Winterveld mine, for example, a homogeneous tabular coarse pyroxenite inclusion 5 inches long and 2 inches thick is directly in line with a homogeneous fine-grained pyroxenite inclusion 13 inches long and 1½ inches thick. Both inclusions lie parallel to the contacts of the seam. The gap between the ends of the inclusions is only 2 inches. There is no evidence of alteration by the chromitite, of displacement, or of alteration subsequent to formation of the chromitite.

Evidence of the kind cited, plus the fact that the inclusions are of several

lithologic types, confronts the hypothesis of selective replacement with a difficult dilemma. In order to account for the variety of inclusions and for aligned inclusions of contrasting lithology, it must be assumed that the horizon later replaced by chromite consisted originally of layers that were of contrasting lithology or were differentially silicated prior to chromite introduction, and also that certain single layers were differentially silicated. This *heterogeneous* assemblage must then be replaced in such a way that a *homogeneous* chromitite seam results over a distance measured in miles. In other words, the process of replacement is required to be highly selective with respect to the rocks overlying and underlying the chromite horizons but unselective in its operation within that horizon.

The veins of chromite in inclusions in the Steelpoort and Leader Seams bear on the problem. The veins indicate that fracturing preceded or attended development of chromite and that chromium was in a sufficiently mobile state to be precipitated in the fractures. It seems strange under these circumstances that chromite veins extending into the enclosing pyroxenites are nowhere to be found, but it is conceivable that deformation might have been confined to specific horizons to the exclusion of others. Petrographic evidence, cited in a later section, shows that the chromite of the veins has crystallized after the component grains of the inclusions. We must therefore assume that either the textural relations of chromite to pyroxene pseudomorph the textural relations of chromite to an original sediment subsequently silicated, or that a pre-existing rock was converted to pyroxenite before formation of chromite. No evidence for either has been discovered.

Even if we dismiss the difficulties discussed above, the presence of inclusions of other types of rocks in all types of rocks of the lower part of the Critical Zone must still be explained. If the heterogeneity of the Critical Zone reflects that of an original pile of sediments, how can one account for the varied lithology and occurrence of these inclusions? The sediments of the upper part of the Pretoria series in this area (10, p. 148) were predominantly sandy or finer clastics. It seems most unlikely that pebbles and boulders would be found in all the members of such an assemblage, in many places far above contacts with possible source rocks.

The hypothesis of selective replacement of an original varied pile of sediments is chiefly attractive as a possible explanation of the pseudostratification of the Critical Zone. As an explanation of other features of the zone it raises as many problems as it solves. The writers are therefore led to reject large-scale metasomatism as an explanation of the features observed and to seek an explanation in magmatic processes.

The hypothesis of successive injection of contrasting submagmas produced by differentiation in depth is due to Reuning (29, 30). We reject it for the reasons so clearly stated by Wagner (41, p. 46) and by Hall (15, p. 182). The lack of intrusive relationships among different units, the parallelism and constancy of many of them over long distances, and gradations among the various rock types are contrary to the concept.

Gravitative differentiation, the third hypothesis in the list, has received careful attention from the great majority of students of the Bushveld. Dis-

cussions through 1931 were concisely summarized by Hall (15, p. 279–281). Gravitative differentiation is still the preferred explanation, but it is generally recognized that fractional crystallization and gravitative differentiation must have been complicated by other processes.

When the features discussed in the present report are examined against this hypothesis, a number of the features observed are explainable. The hypothesis accounts satisfactorily for the persistence of units and for parallel, even contacts. It can account for both sharp and gradational contacts. It accounts for contrasts between rock types and for concentrations of certain minerals in particular layers. A continuous, uninterrupted course of fractional crystallization and gravitative settling (or rising) of early-formed crystals cannot account, however, for repetitions of rock types, and it is necessary to assume intermittency and reversal of cooling curves, or movement of fresh supplies of norite magma into the chamber. The possibilities involved have been discussed by Wagner.

Even as modified by Wagner, however, the theory cannot account for inclusions of one rock type in another, for the apparent derivation of inclusions elsewhere than from the immediate walls, or for apparent disconformities between layers. These can be explained, however, on the basis that the still liquid portion of the magma was intermittently in motion, with currents at times strong enough to erode and occasionally to disrupt layers of earlier-formed material. Our view is therefore that the pseudostratification of the Critical Zone is due to differential mechanical sedimentation of chemically precipitated crystals in the magma. Our findings therefore agree with those of Schmidt (35), who has presented striking evidence for the activity of magmatic currents during the formation of the Merensky Reef in the Rustenburg area. In a magma in motion, differential magmatic sedimentation controlled by variations in velocity of magmatic currents would account for alternation of rock types without resort to reversal of cooling curves, intermittency of crystallization, use of isogeotherms, or successive heaves of magma.

Magmatic currents have been invoked in explanation of the layered rocks of the Duluth gabbro (14), the Stillwater Complex (16), and the Skaergaard Complex (39). Wager and Deer have discussed the process of magmatic sedimentation in great detail. Hess called on disturbance of the normal state of quiescence in the magma by short epochs of mild but irregular turbulence to account for small-scale rhythmic banding in the Stillwater Complex. However, he attributed large-scale banding to progressive changes in the phases crystallizing. He stated that the occurrence of a chromite band or bands in the ultramafic zones of the Stillwater and Bushveld Complexes is due to the crystallization and settling of chromite at a particular instant or instants in the course of crystallization of the mafic magma. Wager (38) has suggested that a series of convection cells was in operation in the Bushveld Complex during crystallization. Certainly currents operative on a large scale would be necessary to produce layers of such regularity and great extent as the chromitite seams discussed in the present paper.

There are other features of the chromite seams themselves, however, that require explanation. The most important are the thin selvages around

inclusions and the presence of veins in some of the inclusions. The veins are the principal stumbling block. The possibility of mechanical injection of the chromite must be considered, but here we are confronted with the fact that apart from the veins themselves, there is no sign of deformation either in the inclusions or in the enclosing chromite. The narrowness of most of the veins is also a difficulty. We seem forced to conclude that during the consolidation of the Steelpoort Seam, part at least of the chromium was present in a liquid phase.

There are three ways in which a chrome-rich liquid might conceivably arise: (1) by accumulation of chromium and iron in the residual liquid at a late stage of crystallization of the parent magma, (2) by separation of an immiscible liquid rich in chromium and iron, and (3) by re-solution of settled chromite crystals.

The first possibility has been discussed by Hall (15) and by Bateman (2) as a means of accounting for the titanomagnetite layers of the main norite zone of the Bushveld complex, and Bateman (2, p. 413–14, 420) has suggested that the chromitite seams may have formed from such residual liquids. The petrogenetic problems involved in this hypothesis are discussed in a subsequent section. For the moment, it is only necessary to examine the hypothesis against the field evidence.

Let us assume that formation of a residual liquid enriched in Fe and Cr is possible. The middle member of the Steelpoort Main Seam consists of about 95 percent chromite (S. G. 4.4) and 5 percent combined bronzite and plagioclase. The specific gravity of the rock is close to 4.4. Allowing a 10 percent reduction in specific gravity for conversion to the liquid state, which is probably generous, the liquid would have a specific gravity of about 3.9. The specific gravity of bronzite is about 3.37, hence pyroxene crystals and pyroxenite inclusions should be displaced upward in a residual liquid of the necessary composition. This would account for accumulation of a layer of Cr-rich liquid. But why is it that the pyroxenite inclusions are found from top to bottom of the chromitites and are not concentrated at any particular level? How shall we explain the fact that the middle member of the Steelpoort Main Seam everywhere grades *both upward and downward* into pyroxenite? It seems unlikely that gravitative displacement of pyroxene would produce the same distribution of pyroxene relative to chromite both above and below. Sharp contacts of the middle member with persistent pyroxenite partings must be explained at the same time. Even if lateral movement of the residual liquid took place, the combination of features cited is difficult to understand. Magmatic sedimentation, with variations in ratio of pyroxene deposited to chromite deposited in response to fluctuations in current velocity, seems to offer a simpler and more satisfactory explanation of partings, distribution of inclusions, and gradational contacts of the middle member. Immiscible liquid segregation poses essentially the same mechanical problems as residual liquid segregation, but neither hypothesis can be dismissed solely on the basis of field evidence.

The final possibility is re-solution of crystals of chromite deposited upon a pyroxenite floor as suggested by Sampson (33). Pyroxene and chromite

must be assumed to be settling in a noritic magma, the ratio of pyroxene to chromite varying with time. The chromitite seams would presumably be formed at times when the ratio of chromite settling to pyroxene settling is very high. If settling brings crystals of chromite into a hotter zone, some re-solution must take place. Re-solution of much of the chromite, however, is not consistent with the field relations, since then the same problems arise as those presented by residual liquid accumulation and immiscible liquid segregation. There must be at least enough, however, to account for deposition of chromite along fractures in the inclusions and for any other chromite present that can be shown to have formed in place. It may well be objected that if fracturing and veining of inclusions have taken place, then why are there no veinlets of chromite in the walls? A possible answer is that the fracturing of inclusions was produced when the inclusions were torn from pyroxenite elsewhere and that the inclusions were subsequently carried into their present locations. The alternative is to suppose that sporadic resumption of the settling of pyroxene crystals gave rise to partings of pyroxenite, and that some of these were dismembered by lateral movement of the enclosing chromitite at the stage at which it was still partly liquid.

The partings are a special problem. Sharp contacts of some with the middle member of the Steelpoort Seam stand in marked contrast to the gradational character of the upper and lower members enclosing the seam. The partings, furthermore, are of very limited extent compared to the seams. Local, temporary slackening in the velocity of magma currents, with deposition of pyroxene over restricted areas, seems the most logical explanation. This explanation is more consistent with physical chemistry than variations in the relative rates of crystallization of chromite and pyroxene.

CONCLUSIONS FROM FIELD EVIDENCE

Field evidence appears to leave only three possibilities for the mode of formation of the chromitites in pyroxenite: (1) residual liquid accumulation, (2) immiscible liquid segregation, and (3) differential magmatic sedimentation of chromite and pyroxene, with partial resolution of chromite. These possibilities must now be examined against the petrographic characteristics of the chromitites and associated rocks.

PETROGRAPHY OF THE STEELPOORT MAIN SEAM, THE LEADER SEAM, AND ENCLOSING PYROXENITES

General Statement.—The following account is based on study of more than 100 thin sections and polished surfaces of specimens from the Steelpoort Main Seam and Leader Seam, and from the enclosing pyroxenites. Samples were taken from drill cores and hand specimens. Petrographic studies have been supplemented by chemical analyses of purified samples of chromite.

Mineral Composition.—The rock sequence studied in detail begins with the pyroxenite above the Leader Seam and extends to the pyroxenite beneath the Steelpoort Main Seam. Figures 26 to 41 are negative photographs[1] of

[1] Figures 26 to 41 were made as follows: The thin section to be photographed was placed in a photographic enlarger, and the image of the thin section was projected directly on photographic printing paper. The developed paper is the negative photograph, which gives the same effect as a true negative.

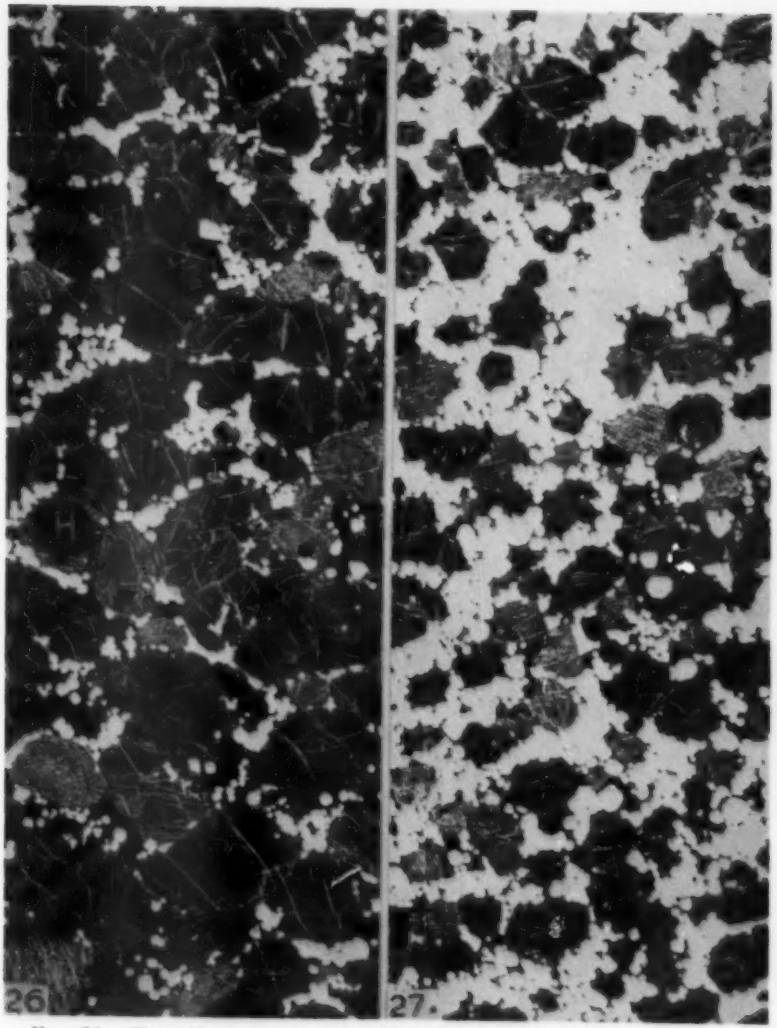


FIG. 26. Chromiferous pyroxenite, 26 inches below base of middle member, Steelpoort Seam. Subhedral to rounded crystals (gray with cracks) with chromite crystals and aggregates of crystals (white) and plagioclase (black). H—hole in section. Bronzite is euhedral against plagioclase, indented against chromite. Negative photograph, × 12.

FIG. 27. Low-grade chromitite, basal part of lower member, Steelpoort Seam. Minerals as in Figure 26. Boundaries of bronzite crystals (gray) against chromite (white) are indented; some chromite crystals appear partly or wholly enclosed in margins of bronzite crystals. Some boundaries suggest mutual interference due to enlargement of settled crystals. Plagioclase (black) mostly occupies tiny interstices of chromite crystals. Negative photograph, × 12.

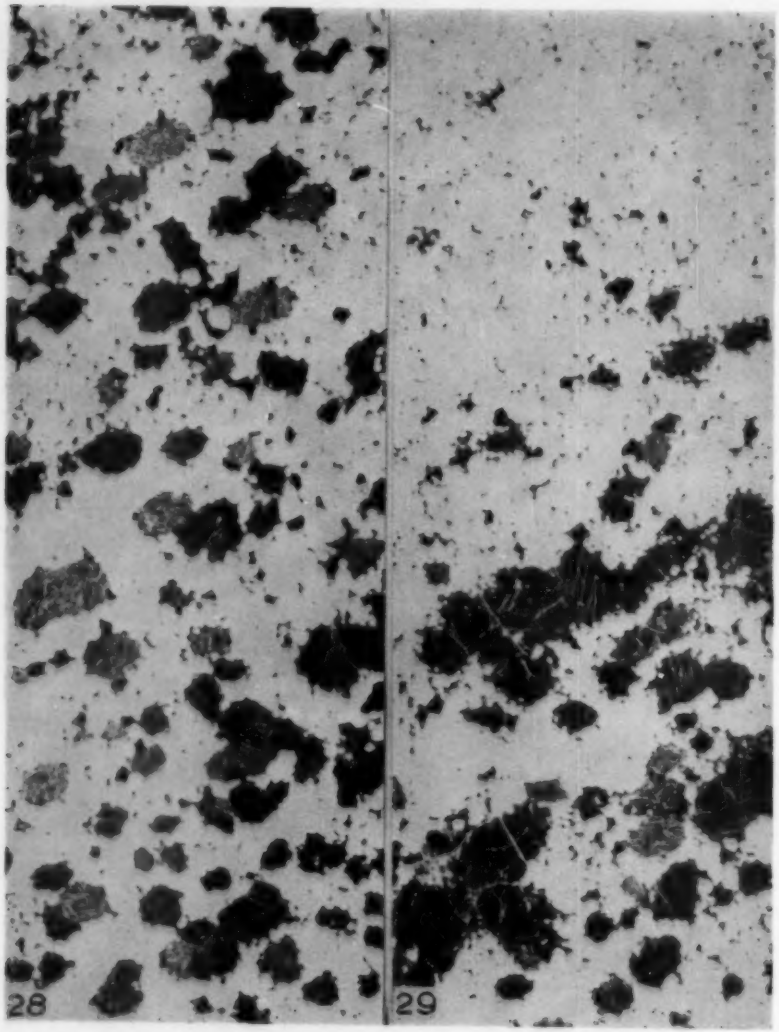


FIG. 28. Impure chromitite, upper part of lower member, Steelpoort Seam, 2 inches below base of middle member. Bronzite crystals (gray) smaller than in Figures 26 and 27, and highly indented against chromite crystals (white). Plagioclase (black) occupies tiny interstices of chromite aggregates. Negative photograph, × 12.

FIG. 29. Gradational contact of lower and middle members, Steelpoort Seam. Note disappearance of bronzite crystals (gray) upward and rapid increase in proportion of chromite upward across contact. Plagioclase (black) occupies tiny interstices of chromite aggregates. Negative photograph, × 12.

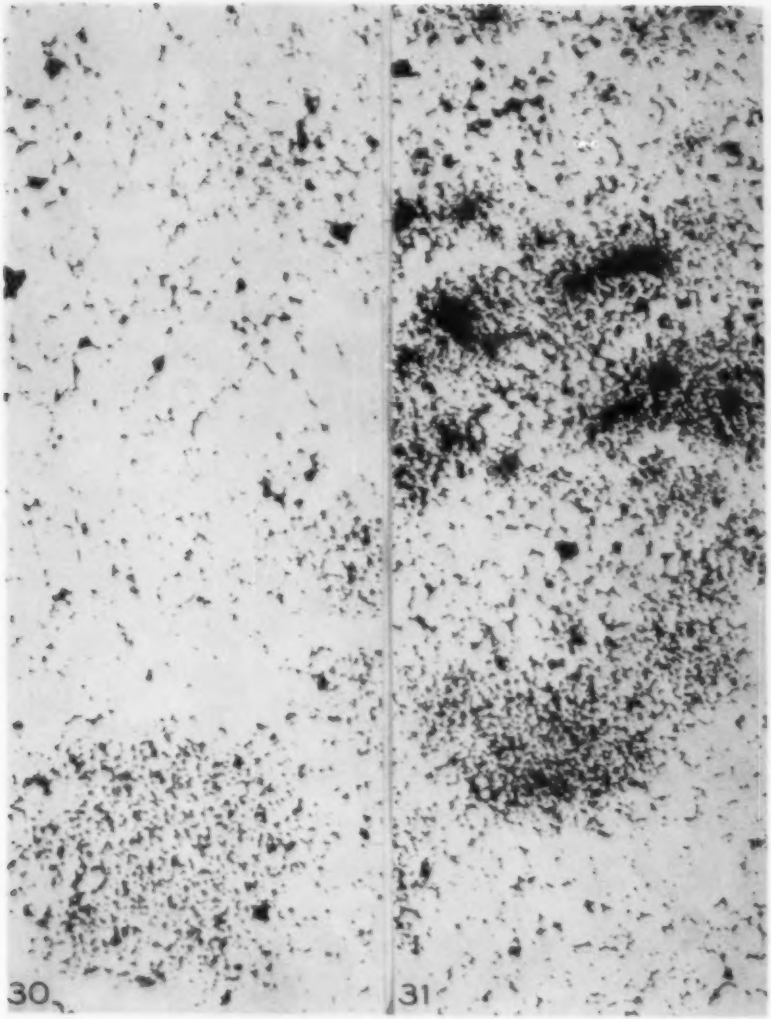


FIG. 30. Chromitite, middle member of Steelpoort Seam, 26 inches above base. White is chromite. Speckled patches toward bottom are large bronzite crystals crowded with inclusions of chromite. Tiny black areas elsewhere are interstitial plagioclase. Negative photograph, × 12.

FIG. 31. Contact of middle and upper members, Steelpoort Seam. Speckled patches are large, poikilitic bronzite crystals, which have non-poikilitic nuclei in upper part. Tiny black areas elsewhere are interstitial plagioclase. × 12.

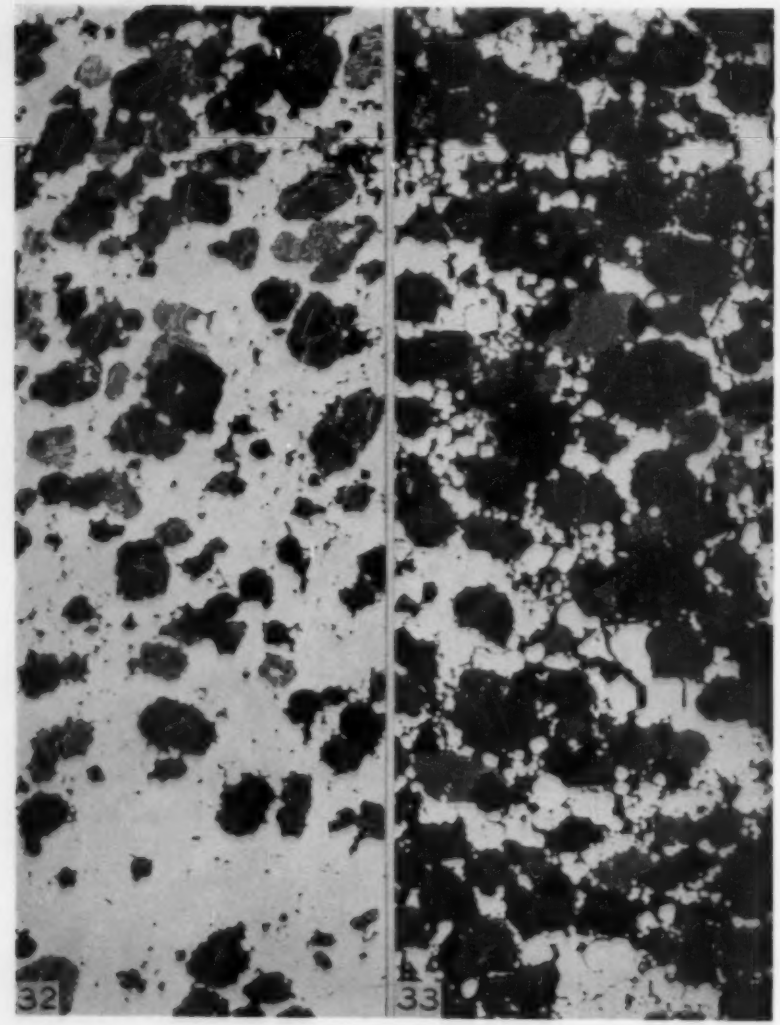


FIG. 32. Impure chromitite, upper member, Steelpoort Seam, 4 inches above middle member. Pyroxene content increases upward and the textural pattern is essentially the same as that of Figure 28. Negative photograph, × 12.

FIG. 33. Impure chromitite at top of upper member of Steelpoort Seam, 10 inches above middle member. Compare textural pattern with that of Figure 27. Negative photograph, × 12.

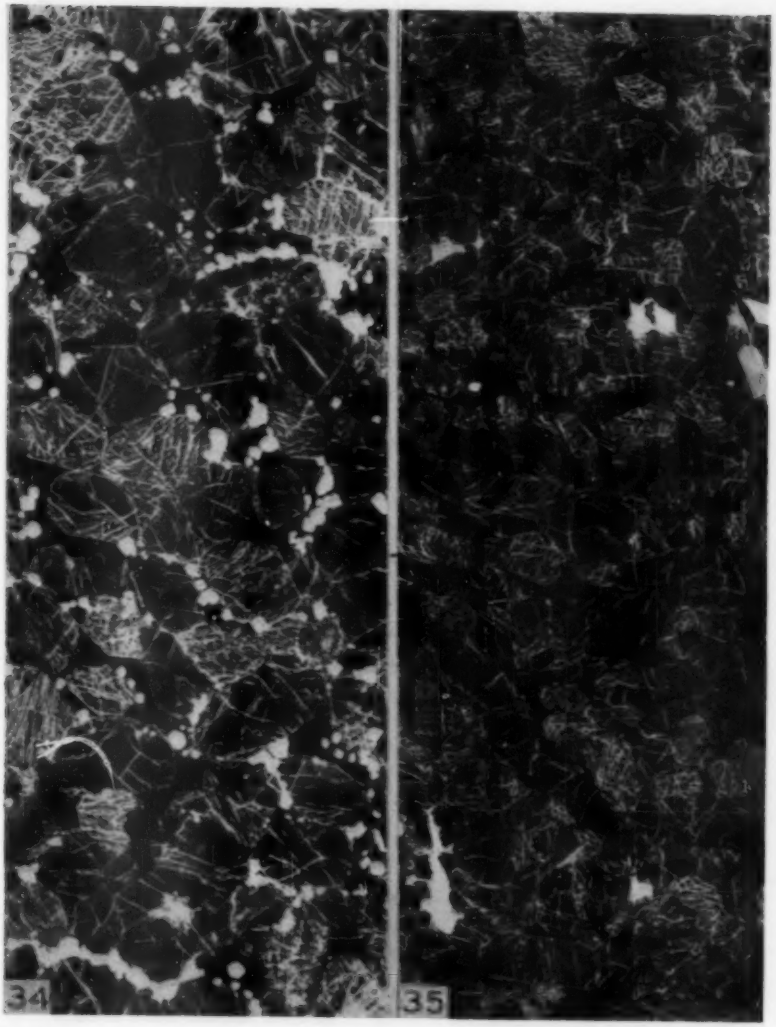


FIG. 34. Pyroxenite, 19 inches above top of middle member, Steelpoort Seam. Compare textural pattern with that of Figure 26. Negative photograph, × 12.

FIG. 35. Pyroxenite, 25 inches above middle member of Steelpoort Seam. A few small chromite crystals are present. Larger light gray and white grains are biotite. Negative photograph, × 12.

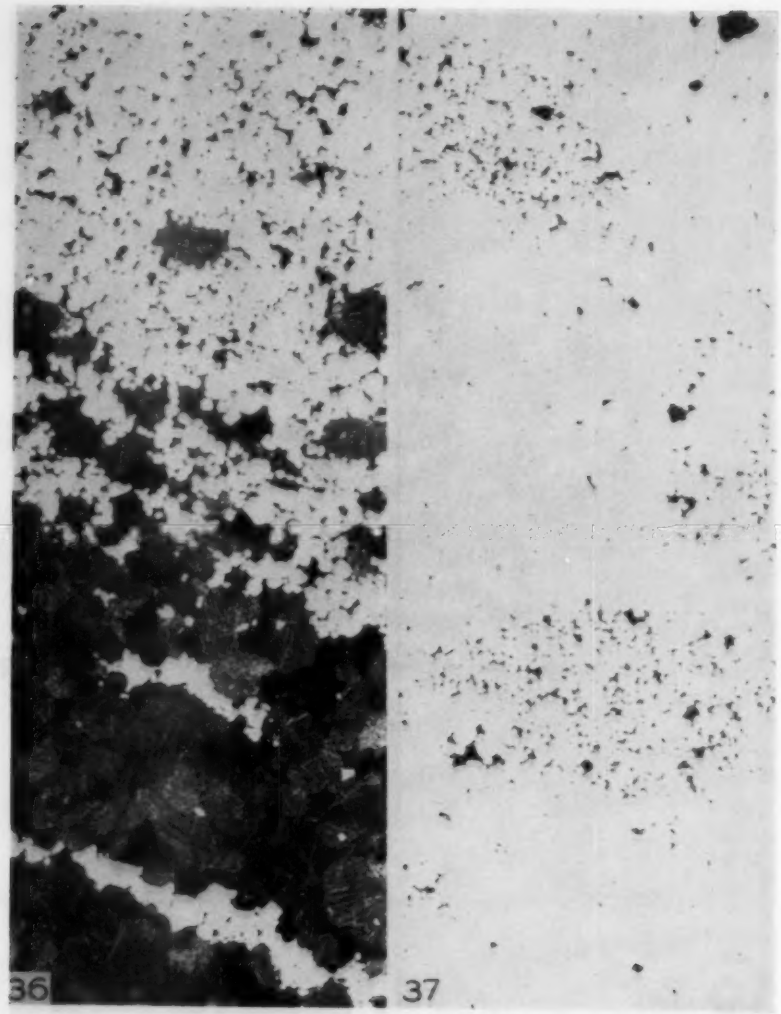


FIG. 36. Contact of Leader Seam with underlying pyroxenite. Note lenticular aggregates of chromite crystals (white) in pyroxenite beneath the contact. The contact is a rapid gradation; bronzite crystals (gray) become less numerous upward. Negative photograph, × 12.

FIG. 37. Chromitite, 9 inches above base of Leader Seam. Each speckled area marks a poikilitic crystal of bronzite. Compare with Figure 30. Negative photograph, × 12.

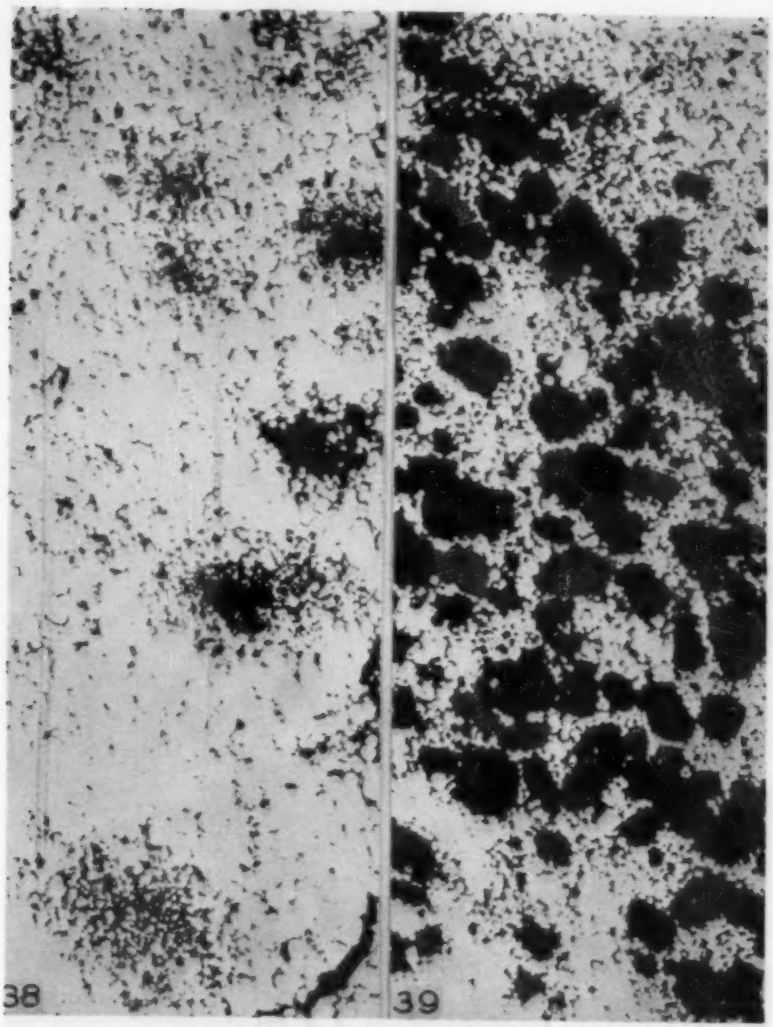


FIG. 38. Gradational contact of lower and upper members, Leader Seam. Speckled area below is a large poikilitic crystal of bronzite; similar crystals in the upper member mostly have non-poikilitic nuclei. Negative photograph, × 12.

FIG. 39. Impure chromitite, upper member of Leader Seam, immediately above contact shown in Figure 38. Note highly indented margins of bronzite crystals and layering due to variations in chromite-pyroxene ratio. Negative photograph, × 12.

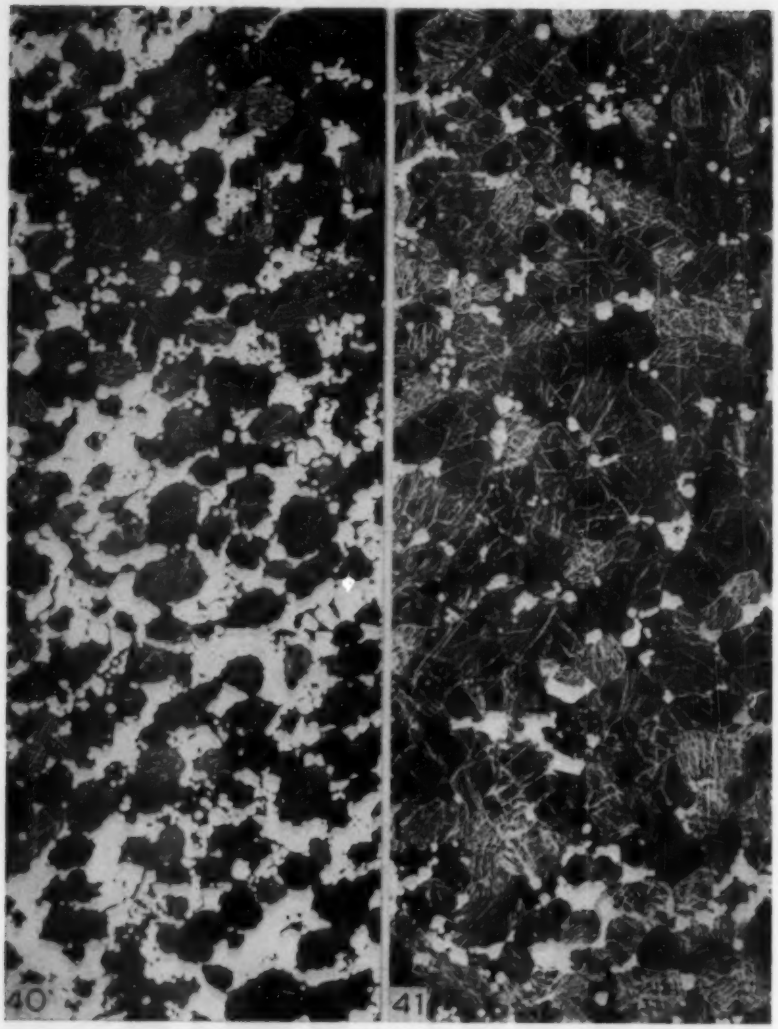


FIG. 40. Impure chromitite grading upward into chromiferous pyroxenite at top of Leader Seam, 2 inches above top of lower member. Compare with Figure 33. Negative photograph, × 12.

FIG. 41. Chromiferous pyroxenite 5 inches above top of lower member of Leader Seam. Compare with Figure 26. Negative photograph, × 12.

thin sections cut from a diamond drill core that gives a continuous section across the sequence. The photographs are selected so as to show the progressive changes in mineral proportions and texture upward through the section, and the photographs are given in the order of upward sequence. In each case, except for Figure 39, which is tilted so that dip of layering is exaggerated, the long dimension of the photograph is parallel to the core axis, and the top of the photograph is the top of the piece of core represented. Changes in mineral proportions from top to bottom of this section are shown quantitatively in Figure 42. Modes were determined from thin sections by use of the Chayes point-counter. The sections were cut from core from a diamond drill hole west of the Jagdlust mine, core recovery from which was 100 percent. The locations of thin sections studied are shown in the figure. Comparison with thin sections cut from other drill cores and from numerous hand specimens indicates that the core discussed is representative.

The modal analyses given in Figure 42 have certain limitations of accuracy. In any given thin section, the minor constituents are unevenly distributed. In thin sections of chrome-rich rock, in particular, pyroxene and plagioclase are unevenly distributed. The totals of the two minerals for chrome-rich horizons are therefore more significant than the individual percentages. Second, the distribution of chromite in the low-grade zones enclosing the main chrome seam is somewhat streaky on a small scale. The curves therefore do not show as smooth a transition from pyroxenite to chromitite as would be expected from exposures of the zone in the field. Clinopyroxene and biotite similarly show an erratic distribution that is reflected in irregularities of the curves of Figure 42. A third limitation is due to variations in the chromitite seams. In some places, the Leader Seam has a half-inch to inch parting of pyroxenite just below its top. Partings and inclusions are likewise found in places in the Steelpoort Main Seam. A final limitation is that a half-inch transition zone underlies the Leader Seam. This zone is too thin to be sampled adequately in thin section and is therefore not accurately reflected in Figure 42.

Despite its limitations, the chart expresses adequately the significant trends in composition through the section. The pyroxenites enclosing and separating the two seams contain 1 to 12 percent chromite. Rhombic pyroxene is by far the dominant mineral of the pyroxenites, plagioclase ranges between 3.2 and 23 percent, chromite forms 0.1 to 16.7 percent, and clinopyroxene and biotite range from 0 to 5.6 percent. The maximum content of biotite in any one section is 2.5 percent, and in most sections the content is less than 1 percent.

The Pyroxenites.—The pyroxenites (Figs. 26, 34, 35, 41) are essentially meshworks of stubby to elongate prisms of bronzite with plagioclase and chromite occupying the interstices. Where chromite crystals are numerous, they form a rudimentary second-order meshwork, with plagioclase occupying the interstices (Fig. 25). Bronzite crystals are euhedral to slightly rounded against plagioclase, but anhedral where in contact with one another or with chromite. In places the prisms show a rough orientation parallel to the pseudostratification; elsewhere they are haphazardly oriented. The crystals are mostly of the type showing interlaminated orthopyroxene and clinopyrox-

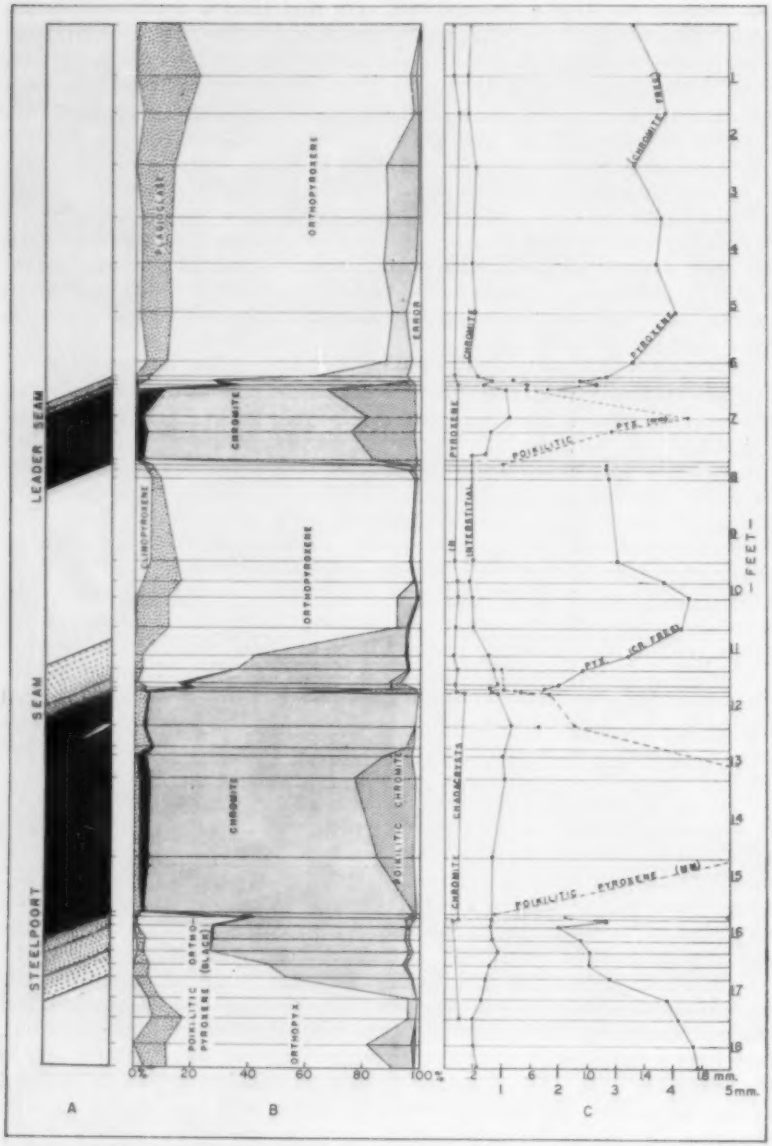


FIG. 42. Section of Steelpoort and Leader chromitite seams and enclosing pyroxenites as shown in a continuous drill core from Farm Jagdlust. A—graphic log of drill core. B—variations in mineral proportions as indicated by modal

ene (18, 19), but for brevity's sake are termed "bronzite" in the present paper. Many crystals are laminated from edge to edge, but some have thin unlaminated selvages.

The exact pattern of bronzite depends on the ratio of bronzite to chromite. This may be seen by comparing Figures 26 and 41 with Figures 27 and 40. As the content of chromite rises, the outlines of the bronzite crystals become more ragged, owing to more numerous interruptions by chromite crystals. These lie along contacts between adjacent bronzite crystals or partly occupy indentations in the bronzite crystals along contacts of bronzite with plagioclase.

Chromite forms single euhedral or slightly rounded crystals or clusters of grains that are anhedral against one another. In a few sections, grains or small aggregates can be found that are interstitial to bronzite and molded against bronzite, but these are rare. Chromite grains are euhedral to slightly rounded, and present slightly rounded outlines against bronzite with which they are in contact. Chromite grains in aggregates interstitial to bronzite are anhedral against one another, but outlines of aggregates against bronzite are uneven, being predominantly the sums of crystal faces of the component grains (Fig. 43). In places, groups of chromite crystals occur in short chainlike structures in plagioclase. An unusually well developed example is shown in Figure 44.

Scattered crystals of chromite occur as inclusions in bronzite. Nearly all are at or close to the peripheries of the bronzite grains, and it seems evident that most of them are only apparent inclusions; i.e., grains of chromite partially embedded in the margins of bronzite grains but cut by the plane of the thin section in such a way as to appear to be completely surrounded by bronzite.

Variations in average maximum diameter of bronzite and chromite crystals are shown in Figure 42. The range of average maximum diameter in the typical pyroxenites is narrow.

Plagioclase (An_{85}) occurs largely as crystals poikilitically enclosing bronzite and chromite. It forms crystals up to 9 mm in diameter, but the average maximum diameter in any one section is between 3 and 5 mm.

Clinopyroxene (diallage) occurs as scattered crystals poikilitically enclosing rounded bronzite crystals. It takes the place of plagioclase in the rock fabric but appears to have formed by a reaction involving bronzite. Chromite has precisely the same relations to clinopyroxene as it does to plagioclase.

Biotite is irregularly scattered through the pyroxenites (Fig. 35). Its distribution is unrelated to that of chromite. It forms irregular grains and clusters of flakes that take the place of plagioclase in the rock fabric. Where biotite and bronzite are in contact, bronzite is rounded and locally embayed. Biotite has developed in places by replacement of plagioclase or bronzite along

analyses of thin sections. C—variations in average grain size of pyroxene and chromite as indicated by measurements of maximum diameters of grains: grain sizes of chromite and non-poikilitic pyroxene in tenths of a millimeter (upper scale); grain sizes of poikilitic pyroxene given in millimeters (lower scale). In B and C, horizontal lines give positions of thin sections analyzed. Average grain size of poikilitic pyroxene in the thin section below 13 feet is 6.0 mm, in the thin section above 15 feet 5.2 mm.

fractures, and locally even chromite is marginally replaced by biotite. Biotite is evidently a late mineral.

The time significance of the textural relationships of the minerals of the pyroxenite must now be appraised. It seems clear that plagioclase and clinopyroxene crystallized after pyroxene, filling whatever spaces were left after crystallization of bronzite or, in the case of clinopyroxene, partly by

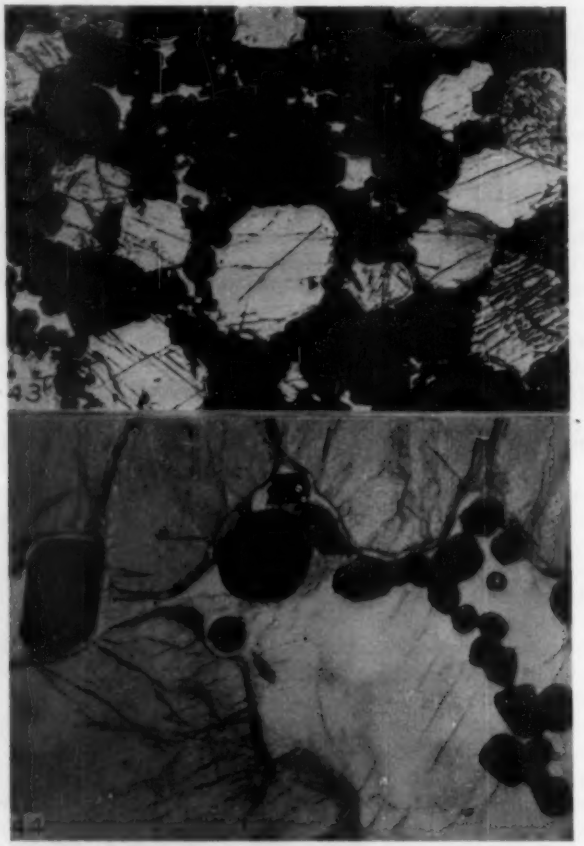


FIG. 43. Photomicrograph of low-grade chromitite from upper member of Steelpoort Seam, showing relations of bronzite to chromite. Large gray grains with cleavage cracks are bronzite, black is chromite. Small irregular areas of lower relief are plagioclase. × 20.

FIG. 44. Photomicrograph of pyroxenite above Steelpoort Seam. Bronzite, gray with high relief; chromite, black, forming rudimentary chain of crystals in plagioclase (white, lower relief). Note selvages of plagioclase separating some of chromite crystals from bronzite. Crossed nicols, × 55.

marginal replacement of bronzite. The relationships of chromite to bronzite, however, are open to argument, and one special feature of their textural relationships requires discussion. Most of the chromite crystals marginal to bronzite are directly in contact with bronzite, but some crystals (Fig. 44) are separated from bronzite by thin films of plagioclase. Sampson (33, p. 129, and Fig. 11), has interpreted this feature as evidence that plagioclase and chromite formed by replacement of bronzite. To us, it is evidence to the contrary. The form of the plagioclase is controlled by the shape of the boundary between chromite and bronzite, indicating that both minerals were formed prior to development of plagioclase. The space occupied by plagioclase seems more reasonably interpreted as formed by reaction between bronzite and interstitial liquid, plagioclase being a by-product of the reaction or following closely upon it. In support of this, Figure 42 shows that the proportion of chromite in pyroxenite does not vary directly with the proportion of plagioclase, in fact, the variation in chromite is more nearly inverse to the variation in plagioclase content. Furthermore, precisely the same relations to bronzite and chromite are shown by biotite and clinopyroxene. Yet neither mineral shows any relation in distribution to chromite, and biotite is clearly later than plagioclase.

The three hypotheses of origin considered tenable on the basis of field evidence must now be re-examined. If the interpretation of textural features given is correct, then as crystallization of the pyroxenites progressed, the interstitial liquid became enriched chiefly in the constituents of plagioclase. Development of a residual liquid rich in Cr and Fe is not indicated. This conclusion is consistent with the differentiation pattern of the Bushveld Complex as a whole. The Cr_2O_3 content of the Bushveld magma can only be surmised, but from what is known of the composition of the noritic rocks, it probably was less than 1 percent. In the 6,000 feet of pyroxenites and peridotites underlying the Steelpoort Seam on Jagdlust, chromite is a persistent accessory mineral, and chromite-rich rocks are present at horizons beneath the Steelpoort Seam. Furthermore, iron was being removed steadily during crystallization of the pile, in bronzite and sometimes olivine. The residual liquids must have been progressively enriched in Ca, Na, Al, and SiO_2, not in Cr and Fe.

The hypothesis of liquid immiscibility is difficult to appraise. All we can say is (1) that if an immiscible Cr-rich liquid phase appeared, it was dispersed through the silicate liquid phase and (2) that crystallization of the Cr-rich liquid preceded crystallization of plagioclase, clinopyroxene, and biotite.

On the other hand, the textural relationships of bronzite, chromite, and plagioclase are readily explained by mechanical deposition of settled bronzite and chromite crystals, followed by crystallization of interstitial liquid. Some parts of the sequence of events involved, however, are clearer than others. Plagioclase, clinopyroxene, and biotite clearly formed in place. The evidence for this is quite satisfactory. It also seems clear that bronzite and chromite are the earliest-formed minerals, but one cannot be too precise in describing the mechanism. The main accumulation of bronzite and chromite would

have to be accomplished by mechanical deposition, but this does not mean that all the bronzite and all the chromite represent settled crystals. Parts of the crystals of both minerals must have formed in place, for the crystals are welded together and interfere with one another. In addition, the sparsely scattered aggregates of minute chromite crystals in plagioclase are suspect of being formed in place. The interstices of settled bronzite and chromite crystals would be occupied by a liquid consisting partly of the constituents of both minerals, and enlargement of settled crystals and even development of new crystals would logically be expected. However, if the magma at the floor was hotter than at the levels of crystallization of the two minerals, partial resolution of settled crystals must have taken place. It is even possible that chromite, in general a minor constituent of the pyroxenites, was entirely redissolved after settling to the floor and is all a product of crystallization in situ. All that the textures really demonstrate is that if chromite formed in situ the crystallization of bronzite overlapped that of chromite. It is essential to realize that the textural patterns of the pyroxenites allow some latitude of interpretation. The patterns reflect numerous factors, of which time is only one. The interstitial relationship of chromite to bronzite, for example, is not an index of relative age. The arrangement would be a natural consequence of the relative sizes of the grains of the two minerals. Normal packing of mechanically deposited grains would require that small, essentially equant grains of a subordinate constituent occupy the interstices of a meshwork of larger, more abundant prismatic crystals.

As a consequence, it would be expected that the content of plagioclase + clinopyroxene + biotite, as an index of the amount of interstitial liquid, would vary inversely with the chromite content, since the combination of large bronzite and small chromite crystals would give better packing and lower porosity than a meshwork of bronzite crystals alone. This inverse relationship seems to be shown in Figure 42. The relationship is not perfect, but inasmuch as the porosity of the meshwork of bronzite and chromite wou'd be influenced also by the degree of preferred orientation of the bronzite, which varies visibly, a perfect correlation is hardly to be expected.

The Lower Member of the Steelpoort Seam.—The features of the lower member of the Steelpoort Seam are important because they show a gradual evolution of the textural patterns of the middle member from the textural pattern of the underlying pyroxenite.

The passage from underlying pyroxenite upward through the lower member is marked by certain textural changes that are a direct function of the gradual increase in the ratio of chromite to bronzite (Figs. 27, 28, 29). As the chromite crystals become more numerous, surfaces of contact between bronzite and chromite are increased, and the bronzite crystals have increasingly indented margins. Marginally included chromite crystals also increase in number. The relations of plagioclase, clinopyroxene, and biotite to bronzite and chromite remain the same. The textural pattern (Fig. 27) is similar to one illustrated by Sampson (33, Fig. 10), but we cannot agree that this pattern is evidence for replacement of bronzite by chromite. The interstitial aggregates of chromite present boundaries against pyroxene that are the

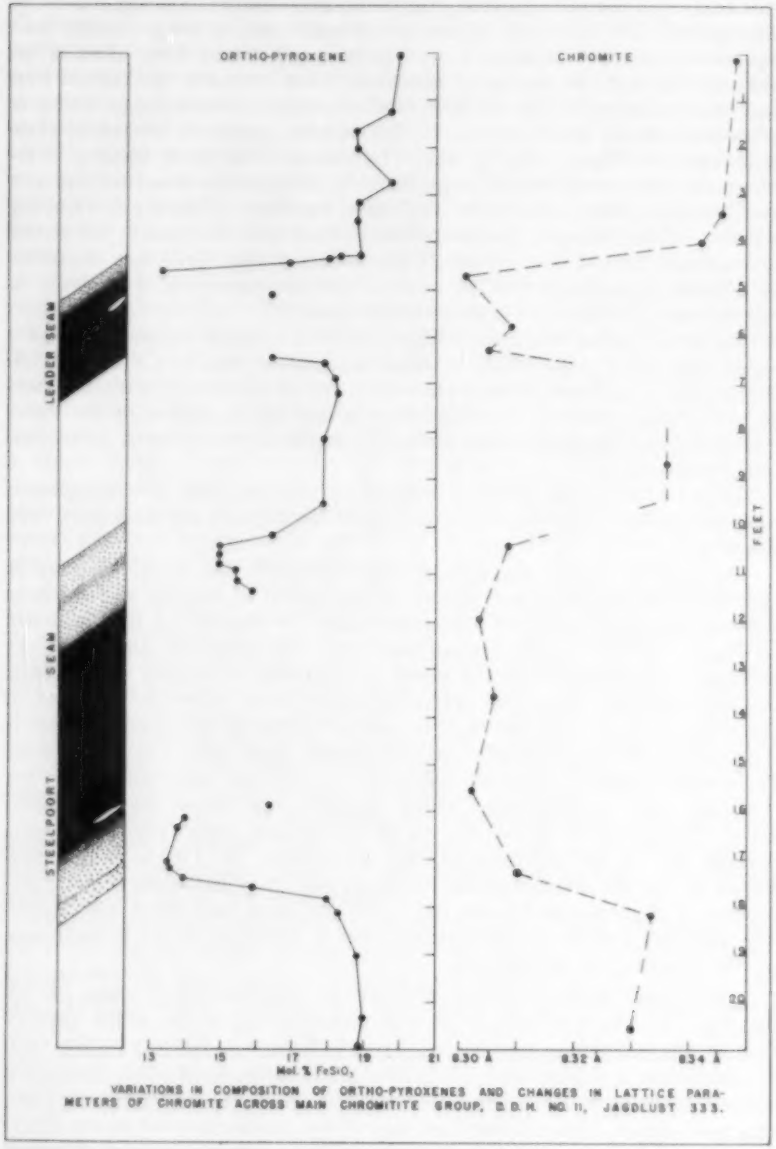
summations of crystal faces belonging to the individual chromite grains of the aggregates. The fact that replacing minerals may develop crystal form against the minerals replaced is well known, and crystal form alone is not evidence for time or process of formation. But certainly the pattern here described is entirely different from that normally produced by corrosion of silicates by late magmatic oxides (2, 36), and the pattern of interstitial chromite from Lala Panzi (33, Fig. 3). The pattern in the lower member of the Steelpoort Seam could readily be produced by overgrowths on settled chromite and bronzite grains sufficient to weld them together. Certainly the welding together of the bronzite grains indicates either that overgrowth on settled crystals was part of the process of formation, or that there was resolution of crystals at points of mutual contact, with accompanying overgrowth at points where crystals were in contact with liquid.

Again the order of crystallization indicates residual accumulation of a liquid rich in the constituents of plagioclase rather than in Cr and Fe. If segregated, it would yield not a chromitite, but an anorthosite with accessory pyroxene and chromite. It seems evident that the formation of the lower member of the Steelpoort Seam cannot be explained on the basis of residual liquid accumulation.

Liquid immiscibility is more difficult to evaluate, and its consideration must be deferred until the middle and upper members of the seam have been described.

As depicted above, the mineral relationships in the lower member in general are consistent with magmatic sedimentation of bronzite and chromite followed by crystallization of interstitial liquid, but there is one feature shown in Figure 42 that appears inconsistent with this mode of origin. If the chromite concentrations are the result of variations in velocity of magmatic currents, then the chromitite layers represent times when the velocities of magmatic currents were too high to permit settling of pyroxene. If this is so, there should be an increase in the average grain size of both pyroxene and chromite upward from the pyroxenite through the lower member of the chromite seam, because with rising velocity only larger crystals should settle. Figure 42 shows that the size of the chromite grains rises irregularly, but the size of the pyroxene crystals diminishes. It will be noted from Figure 42 that the same grain size variations take place *downward* in the upper member of the Steelpoort Seam and in the transition zone above the Leader. The variation is evidently not fortuitous but is definitely related in some way to the concentration of chromite.

The changes in grain size are accompanied by two other changes. First, the Mg : Fe ratio is greater in bronzite and chromite in the lower member than in the underlying pyroxenite. Second, there is a decrease in the ratio of plagioclase + clinopyroxene + biotite to bronzite + chromite, indicating either a decrease in the amount of interstitial liquid or a change in its composition. Again, in the upward passage of the middle member of the Steelpoort Seam into pyroxenite through the upper member, and in the upward gradation (upper member) of the Leader Seam into pyroxenite, these changes



VARIATIONS IN COMPOSITION OF ORTHO-PYROXENES AND CHANGES IN LATTICE PARAMETERS OF CHROMITE ACROSS MAIN CHROMITITE GROUP, D.D.H. NO. 11, JAGDLUST 333.

FIG. 45.

are reversed, hence they too appear definitely related to the process of chromite concentration.

Van der Walt (37) found that in the western part of the Bushveld chromite and pyroxene in chromitites and associated pyroxenites vary sympathetically in composition. Our findings for the sequence studied agree with his. Variations in pyroxene, based on measurements of indices of refraction, are shown in Figure 45. No pyroxene suitable for measurement could be obtained from the actual chromitites, but bronzite in the low-grade zones is richer in $MgSiO_3$ than pyroxene in the pyroxenites. Variations in chemical

TABLE 1

ANALYSES OF PURIFIED CHROMITE SAMPLES

	1	2	3	4	5
Cr_2O_3	47.12%	47.31%	47.31%	46.93%	49.31%
Al_2O_3	15.74	13.88	14.49	11.04	9.49
Fe_2O_3	n.d.	7.84	7.44	n.d.	8.87
FeO	n.d.	20.22	19.03	n.d.	24.35
Total Fe as FeO	25.15	(27.28)*	(25.73)*	29.46	(32.34)*
MgO	11.13	9.21	10.07	9.10	5.90
CaO	0.53	tr.	tr.	0.48	0.00
TiO_2	0.44	0.58	0.58	0.55	0.66
V_2O_5	0.62	0.28	0.28	0.62	0.33
SiO_2	0.12	0.07	0.13	0.22	0.13
Na_2O	0.04	n.d.	n.d.	0.03	n.d.
K_2O	0.03	n.d.	n.d.	0.05	n.d.
MnO	n.d.	0.46	0.44	n.d.	0.16
H_2O	n.d.	0.01	0.08	n.d.	0.08
P_2O_5	n.d.	n.d.	n.d.	n.d.	0.00
Totals	100.92	99.86	99.85	98.48	99.88
Cr:Fe	1.64	1.52	1.61	1.40	1.33
Mg:Fe	.34	.26	.31	.23	.14

* Figure not included in total.

1. Chromite from middle member, Steelpoort Seam, Winterveld mine.
2. Chromite from middle part of upper member, Steelpoort Seam, Farm Jagdlust.
3. Chromite from lower member, Leader Seam, Farm Jagdlust.
4. Chromite from upper member, Leader Seam, Farm Jagdlust.
5. Chromite from pyroxenite overlying Leader Seam, Farm Jagdlust.

Analyses 2, 3, and 5 by C. O. Ingamells, Rock Analysis Laboratory, University of Minnesota. Analyses 1 and 4 by D. McLean, Union Carbide Ore Company.

composition of the pure chromite mineral from five members of the sequence studied during the present investigation are shown in Table 1. The Mg:Fe ratio is highest in chromite from the middle member of the Steelpoort Seam and only slightly lower in chromite from the lower member of the Leader. It is intermediate in value in chromite from the low grade members of these seams, and lowest in chromite from the pyroxenite. It seems evident that chromite varies sympathetically with bronzite through the sequence.

De Wet and Van Niekerk (9) analyzed the pure chromite mineral from each of seven chromitite seams from the eastern and western norite belts and determined the lattice parameters. The parameters range from 8.297 to 8.319 Å. No correlation between the lattice parameters given and composi-

tions of the chromites is apparent. Similar parameters were found for chromites of markedly divergent compositions.

In Figure 45, lattice parameters are plotted for 14 chromites taken from the various members of the Steelpoort and Leader seams and the associated pyroxenites. A systematic relationship between lattice parameter and position in the sequence is clearly indicated, even allowing for inaccuracy of some of the determinations. Lattice parameters are largest for chromites from the pyroxenites, intermediate in value for chromites from the low-grade chromitite members and lowest for chromites from the high-grade chromitite members. Taken together with the chemical analyses of Table 1, the data may indicate that the lattice parameters are controlled by the Fe : Mg ratio, the larger parameters being due to increase in the number of the larger Fe^{++} ions in the lattice. The possible effects of other ions on the lattice parameters, however, cannot be evaluated from present data. The chemical analyses of Table 1 remain the best evidence that chromite varies sympathetically with bronzite through the sequence.

The chemical analyses have several other features of interest. The Cr_2O_3 content of chromite shows little variation in the chromitites, whether low-grade or high grade, but chromite from the pyroxenite overlying the Leader Seam shows a much higher Cr_2O_3 content. The significance of this is not apparent. Al_2O_3 varies sympathetically with the Mg : Fe ratio, whereas from three analyses in which FeO and Fe_2O_3 were determined, Fe_2O_3 and FeO vary antipathetically. For minor elements, additional analytical work is desirable. Titanium, in part at least, is in the form of rutile, which is not removed in the purification process employed. Manganese is probably a constituent of the chromite itself, substituting for Fe^{++}. Vanadium may also be a constituent of the chromite.

Significance of Changes in Grain Size and Mg : Fe Ratios.—Neither changes in grain size of bronzite nor changes in Mg : Fe ratio of bronzite and chromite are consistent with simple magmatic sedimentation, and a supplementary process seems required. Inasmuch as residual liquid segregation is inconsistent with the sequence of mineral formation in either the pyroxenites or the lower member of the Steelpoort Seam, the possibilities of resolution of crystals must now be examined.

If chromite and pyroxene are crystallizing together in a higher zone of the magma chamber, under the influence of a temperature gradient related to the roof of the chamber, then in settling they must pass into a zone of higher temperature below. Some resolution must take place, and part of this must be accomplished during settling. We are concerned, however, only with the resolution of crystals after the crystals reach the floor (i.e., the top of the pile of crystal accumulates). The amount of resolution per crystal will then be a function of several factors: (1) the degree of saturation of the liquid with the minerals involved; (2) the number of crystals of each mineral available per unit volume of mush (settled crystals plus interstitial liquid); (3) the size of the crystals; (4) the rate of sedimentation and hence the time of contact of the crystals with the overlying liquid before burial; and (5) the types

of compounds represented in the settled crystals; i.e., whether simple compounds or solid solutions.

In the present case, no quantitative calculations can be made, but certain qualitative inferences seem reasonable. First, undersaturation of the liquid in both chromite and bronzite is a reasonable possibility on the assumption that temperatures were higher than in the upper part of the magma chamber. Second, the ratio of chromite crystals to bronzite crystals available per unit volume of mush increased during formation of the Steelpoort Main Seam. Third, the initial size of crystals was probably larger at this stage both for chromite and bronzite. The relative rate of sedimentation can also be inferred. If deposition of the chromitite seams is due primarily to differential sedimentation, not to variation in ratio of bronzite crystallizing to chromite crystallizing, then the rate of sedimentation must have been decreasing rapidly during accumulation of the lower member of the Steelpoort Seam. The time during which the crystals were in contact with the overlying liquid, either directly or through diffusion, would therefore be increased. The amount of resolution per crystal should therefore be greater, but the mechanism of resolution is also important. Since both chromite and bronzite are solid solutions, crystallization of each involves reaction of early-formed crystals with liquid, with progressive enrichment of crystals in lower-melting components. Resolution would involve the reverse. The chromite and bronzite crystals subjected to partial resolution should at the same time be enriched in Mg and impoverished in Fe. The writers suggest that the enrichment of chromite and bronzite in MgO relative to FeO in the chromite-rich rocks is due to their slower rate of accumulation with greater opportunity before burial for reaction with overlying liquid, either because they were in direct contact or because they were still within the range of diffusion. The explanation by Van der Walt (37) and Kuschke (23) of the phenomenon of enrichment is not satisfactory. They suggest that at times when chromite was crystallizing in large amount, depletion of the magma in iron, which is required in large concentration in chromite, led to enrichment of bronzite and chromite in MgO. However, a change in relative rates of crystallization is only possible if there is a change in the composition of the magma by addition of new material. Following Lombaard (24) and Niggli and Lombaard (27), they therefore suggest that the Bushveld Complex was formed from successive heaves of magma. This is not a satisfactory explanation for the innumerable repetitions of rock types, the chromitites among them, that are found within short vertical intervals in the Critical Zone.

The smaller size of the pyroxene crystals we suggest may be ascribed to the smaller number of pyroxene crystals per unit of mush, hence the greater resolution per crystal. The chromite crystals, being present now in large numbers, would not be decreased in size so much as the bronzite crystals.

The difference in time of contact with overlying liquid would seem to be a critical factor. Resolution would have no permanent effect either on Fe:Mg ratio or on size of crystals unless the Fe taken into solution were carried away. If it were merely taken into the interstitial liquid of a mush

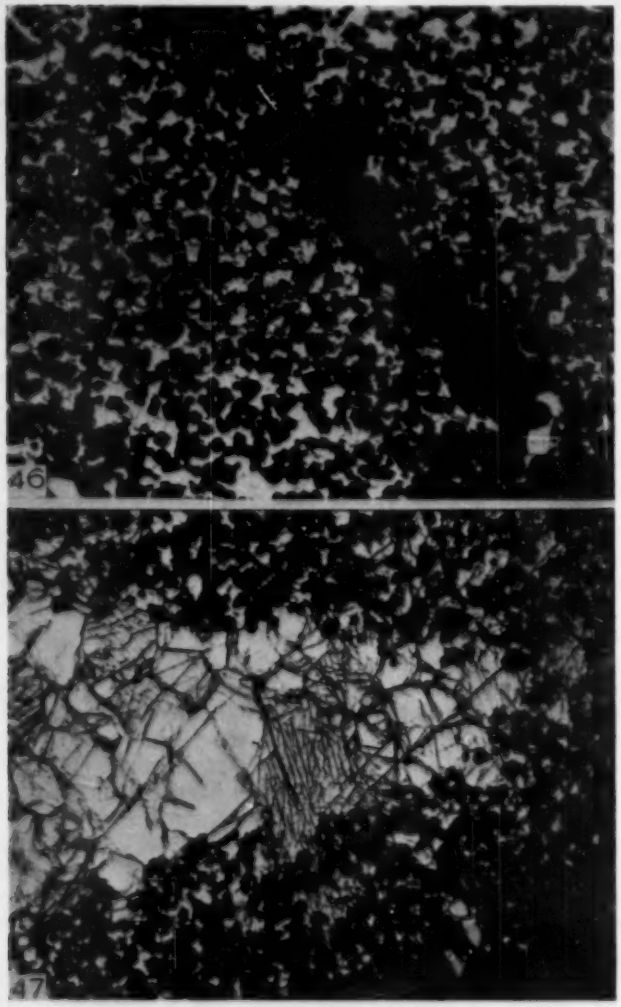


FIG. 46. Photomicrograph of parts of two large poikilitic bronzite crystals (white) enclosing chains of chromite crystals (black). Broad diagonal band of chromite separates the two bronzite crystals. Middle member, Steelpoort Seam, from same thin section as Fig. 30. × 28.

FIG. 47. Photomicrograph of end of inclusion shown in Figure 48 with surrounding selvage. Bronzite white, chromite black. × 22.

and not removed mechanically or by diffusion, then the ultimate crystallization of the interstitial liquid would reverse the process of resolution.

The Middle Member of the Steelpoort Seam.—The contact between the lower and middle members of the Steelpoort Seam (Fig. 29) is marked by the disappearance of non-poikilitic bronzite of the type that characterizes the underlying pyroxenites and the lower member of the seam. The middle member consists largely of three textural elements. One consists of pyroxene crystals poikilitically enclosing chain structures formed by chromite (Figs. 30, 46). The second consists of granular chromite surrounding the chromite-pyroxene intergrowths. The third consists of plagioclase, which is interstitial to the granular chromite and the intergrowths. The plagioclase is no longer in large poikilitic crystals. Plagioclase grains in adjacent interstices of the granular chromite are not in optical continuity. Some of the plagioclase grains, however, enclose tiny chains and partial chains of chromite. Biotite and clinopyroxene are absent. Rutile occurs as a minor accessory. Rutile accounts for part, but probably not for all, the 0.4% to 0.7% TiO_2 shown by analyses.

The percentages of the various components by volume are shown in Figure 42. In this chart, percentages are given separately for granular chromite and for chromite poikilitically included in pyroxene. For the horizon represented by any thin section, the apparent percentage by volume occupied by intergrowths can be obtained by adding the percentage for poikilitically enclosed chromite to the percentage for pyroxene. Thus from the figure, the volume of intergrowths ranges from 0 to 25 percent in various thin sections. Inasmuch as the intergrowths are large and unevenly distributed, and a thin section is not an adequate sample for a given horizon in the member, the average, about 12 percent, is more significant than the range, and the impression given by the chart that the intergrowths are concentrated in certain horizons of the seam is misleading.

The chains are at once a problem and yet undoubtedly a key to the understanding of the origin of the chromitite seams. Wagner (40, p. 323) discussed the chain structures in bronzite in detail. He concluded that the bronzite-chain chromite intergrowths crystallized at the same time as the enclosing granular chromite and that the two settled simultaneously and accumulated together. Sampson (32, p. 639–640, 1932, p. 127) disagreed and concluded that the intergrowths formed by simultaneous crystallization of chromite and bronzite in situ. Our studies provide concrete evidence in support of Sampson's interpretation. The selvages around pyroxenite inclusions in the chromitite have been mentioned in a preceding section. The selvages of twelve inclusions have been sectioned and studied. A typical selvage is shown in Figures 47 and 48. It proves to consist of chain chromite poikilitically enclosed in bronzite. The bronzite in the selvage consists of anhedral crystals, each of which is in optical continuity with an adjacent non-poikilitic bronzite crystal in the body of the inclusion. But whereas the average maximum diameter of bronzite crystals forming the inclusion is 0.64 mm, the average diameter of the marginal partly poikilitic, partly non-poikilitic bronzite crystals is 1.53 mm. The selvages are therefore not due to reaction

replacement of inclusions but are largely overgrowths on the bronzite of the inclusions. Structures of this kind are not found around pyroxenite inclusions in rocks other than chromitites, hence they must have formed during development of the chromitite seams.

The same conclusion is suggested by the sizes of the intergrowths in the seam itself, away from these inclusions, as shown by Figure 42. The units

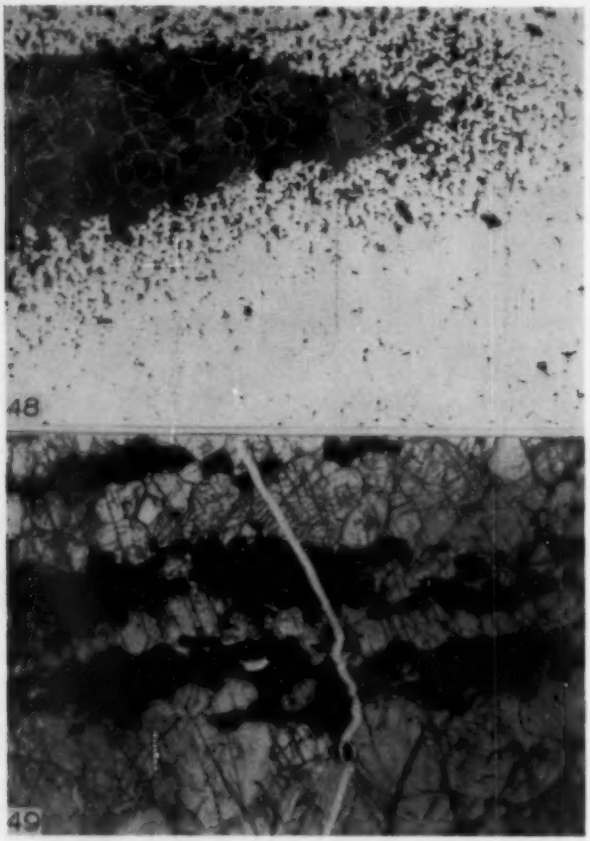


FIG. 48. Pyroxenite inclusion in middle member of Steelpoort Seam. Pyroxene gray, chromite white. Speckled fringe on inclusion consists of poikilitic extensions of bronzite crystals along the margin of the inclusion. Negative photograph. × 10.

FIG. 49. Photomicrograph of veinlets of chromite (black) in pyroxenite (gray) inclusion from middle member of Steelpoort Seam, Winterveld mine. Post-magmatic alteration has developed thin selvages of serpentine along contacts of chromite in this specimen. × 20. White band is crack in thin section.

of bronzite in the intergrowths average 5 to 6 mm in diameter in various thin sections, or about three times the average diameter of the pyroxenes above and below. It therefore seems highly improbable that intergrowths have formed solely by incomplete replacement of settled bronzite crystals by chromite.

Several large inclusions in the chromite-bronzite of the low-grade zones were available from the Jagdlust mine. The compositions of bronzite crystals from two of the inclusions and from the enclosing materials, were determined by immersion methods. Results are shown in Table 2. Bronzite in the inclusions is evidently richer in $FeSiO_3$ than bronzite in the enclosing low-grade chromitite and corresponds in composition to bronzite in the pyroxenites. Bronzite in two very small inclusions in the middle member of the Steelpoort Seam is intermediate in composition between bronzite of the pyroxenites and that of the low-grade zones, but this is probably due to reaction between the inclusions and chromite-rich liquid. It seems evident that the inclusions are xenoliths derived from associated pyroxenites.

TABLE 2

COMPOSITION OF BRONZITE FROM INCLUSIONS AND ENCLOSING LOW-GRADE CHROMITITES

Source of bronzite	% $FeSiO_3$ in bronzite
1. a. Xenolith, Jagdlust	18.5
b. Low-grade chromitite enclosing xenolith	15.5
2. a. Xenolith, Jagdlust	18.0
b. Low-grade chromitite enclosing xenolith	12.0

Veinlets cutting inclusions in the chromitites have been mentioned previously. In hand specimen, these veinlets appear to consist of solid chromite and seem to have sharp contacts with enclosing pyroxenite. Thin sections of the veinlets show, however, that the margins are irregular in detail. Chromite extends into the walls along the boundaries of bronzite grains (Fig. 49). The veinlets are straight as a whole, but they appear to have been controlled in detail by boundaries between bronzite grains. In all veinlets examined, chromite along the margins is anhedral against pyroxene, and pyroxene grains have rounded outlines suggesting resorption. Along the margins of one veinlet, however, poikilitic extensions of bronzite crystals, similar to those along the margins of the inclusions, are developed. The veinlets thus corroborate the evidence from the selvages of the inclusions that chromite crystallized partly in situ.

The veinlets indicate the existence of a liquid phase from which chromite was precipitated, but they also provide rather striking corroboration of the age relation of plagioclase to pyroxene and chromite. The textural pattern of plagioclase indicates that most of it developed by filling whatever spaces were left after crystallization of bronzite and chromite. The tiny chains of chromite in plagioclase, however, may have formed at the same time as plagioclase.

Origin of the Middle Member.—The hypothesis of sedimentation and resolution is a convenient starting point in weighing the origin of the middle

member. Since the base of the middle member is marked by disappearance of non-poikilitic pyroxene, it is necessary to assume that either no pyroxene was settling during its formation or that such pyroxene as did settle was redissolved before burial. It must also be assumed that chromite was partially redissolved at the same time, that the remainder was enriched in $MgSiO_3$ by reaction with the magma, but that resolution and reaction were still incomplete at the time of crystal burial.

The composition of the interstitial liquid subsequent to burial of the chromite is a crucial matter. The intergrowths of pyroxene and chromite, together with interstitial plagioclase, occupy on the average about 12 percent of the volume of the chromitite (Fig. 42). If this material crystallized directly from liquid interstitial to granular chromite, with no addition or loss of constituents by diffusion between the liquid and the magma above, reaction between crystals and interstitial liquid must ultimately yield a liquid having the following approximate composition by weight, omitting trace constituents:

Cr_2O_3	35%
FeO (total Fe)	20
Al_2O_3	16
MgO	12
SiO_2	14
$CaO + Na_2O$	3

These figures make no allowance for chromite deposited as overgrowths welding together the granular chromite crystals surrounding the bronzite-chromite intergrowths. To account for these, a liquid still richer in Cr_2O_3 and FeO would be required.

Assuming for the moment that such a liquid is possible, resolution would ultimately reach a limit, and crystallization of the liquid would then begin. The stages of crystallization are not entirely clear. Undissolved chromite crystals would have to be enlarged and welded together at some stage to give the granular chromite, but whether this would follow or precede crystallization of the intergrowths of pyroxene and chromite is uncertain. A few inferences regarding the intergrowths, however, can be drawn. Chain chromite is present both in bronzite and plagioclase, but there is a difference in habit. Chain intergrowths in single bronzite crystals occupy areas up to 6 mm in diameter. These areas are too large to represent interstices of settled chromite grains. Furthermore, the chain structures are developed in patches, and each patch is an individual bronzite grain or a cluster of two or three tightly fitting grains.

These features suggest that growth of each chain was closely related in time to growth of the host pyroxene and that room for the chain was created by this growth, which caused adjacent chromite crystals to be shoved aside. In contrast, chain structures in plagioclase are small and are limited to spaces that are clearly interstitial to the larger chromite grains. The chains appeared to have formed late. Plagioclase appears to have filled the spaces around them as though the rock was so near complete solidification at this

stage that newly growing crystals could not make room for themselves by displacing neighboring chromite crystals.

The evidence that a liquid phase capable of precipitating chromite existed during the final stages of crystallization of the middle member seems unmistakably clear, as Sampson pointed out (33, p. 127–128). It would be easy to pass to a general conclusion that the entire chromite seam has formed from a liquid produced either by resolution or residual liquid accumulation. This has been done by Fockema and Mendelssohn (13). In a chromitite stratigraphically below the Steelpoort Seam on Farm Apiesboomen these investigators found relationships between chromite and bronzite similar to those described above (Fig. 2, their report). They likewise found veinlets of

TABLE 3

ANALYSES OF NORITES

	1	2	3
SiO_2	51.55	52.05	51.45
TiO_2	0.25	0.21	0.34
Al_2O_3	17.30	17.24	18.67
Cr_2O_3	—	—	—
Fe_2O_3	1.25	0.65	0.28
FeO	6.15	6.65	9.04
MnO	0.10	0.13	0.47
MgO	9.00	8.98	6.84
CaO	11.75	11.37	10.95
NiO	—	—	—
Na_2O	2.65	1.83	1.58
K_2O	0.40	0.40	0.14
P_2O_5	0.10	0.12	0.09
H_2O+	0.55	0.52	0.34
H_2O-	0.15	0.11	0.03
	101.20	100.26	100.22

1. Medium-grained spotted norite, Mamagalies Kraal No. 413. Country rock of the Principal Magnetite Horizon (15, p. 304, analysis IV).
2. Average analysis of common norite of the Bushveld Complex (15, p. 350, analysis I).
3. Average analysis of norite from the chill phase of the Bushveld norite (15, p. 350, analysis IV).

chromite cutting the enclosing rocks. They therefore concluded that the chromitite formed by late gravitative accumulation of a residual Cr-rich liquid. The writers question this conclusion. The textural relations of chromite to pyroxene in the chromitites are only part of a general picture given by the whole sequence of chromitites and associated rocks. The textural relations of members of the sequence as shown in Figures 26 to 41 stand in serial relationship to one another, and no single texture can be interpreted independently of the others. Mineral sequences in the pyroxenites and low-grade chromitites indicate that residual liquids formed at this stage of the evolution of the Critical Zone were rich in plagioclase, not in chromite, and that the high-grade chromitites of the type represented by the Steelpoort Seam cannot have formed by residual liquid accumulation.

The development of a liquid rich in Cr and Fe by resolution, however,

cannot be supported at present by reference to petrography or physical chemistry. Despite the substantial advances in knowledge of silicate systems at high temperatures during the past 25 years, systems involving Cr_2O_3 in the presence of Fe_2O_3, FeO, MgO, Al_2O_3, CaO, and SiO_2 are little known. There is ample petrographic evidence (e.g.; 39, 42, 43, 6) that fractionation of basaltic magma leads to enrichment of the liquid in iron until near the end of crystallization, but in lavas the degree of enrichment is apparently not

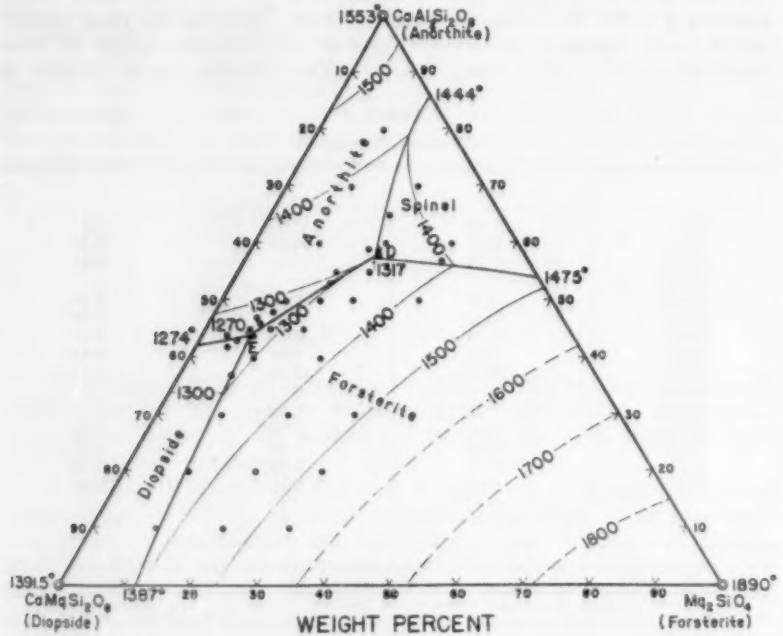


FIG. 50. Equilibrium diagram of the system diopside-forsterite-anorthite (Osborn and Tait, 1952). Light lines are isotherms; heavier lines are boundary curves.

great. In the Keweenawan lavas, total iron calculated as FeO rose slowly during fractionation to a maximum of about 12 percent (6), whereas in the Karroo lavas (43), the extreme was about 16 percent. In the Skaergaard intrusive, the maximum is about 27 percent. In the Bushveld Complex itself, the pattern of differentiation indicates that iron and titanium were concentrated (in titaniferous magnetite) at certain later and presumably lower-temperature stages represented in the Main norite zone. If the origin of the titaniferous magnetites is as explained by Hall (15) and Bateman (2), a liquid phase containing about 70 percent total iron calculated as FeO is possible. The course of differentiation leading to this liquid, however, is obscure. The rock enclosing the titaniferous magnetites (Table 3, analysis 1)

contains no more iron than that reported for the average common norite of the Main Norite zone (Table 3, analysis 2), and the latter contains less iron than the norite of the chill phase. (Table 3, analysis 3).

There appears to be no information from petrography that would indicate the amounts of Cr_2O_3 that can be held in solution in basaltic magma at various stages of fractionation. The occurrence of chromite in basic and ultrabasic rocks has been explained largely in terms of phase relationships in the sys-

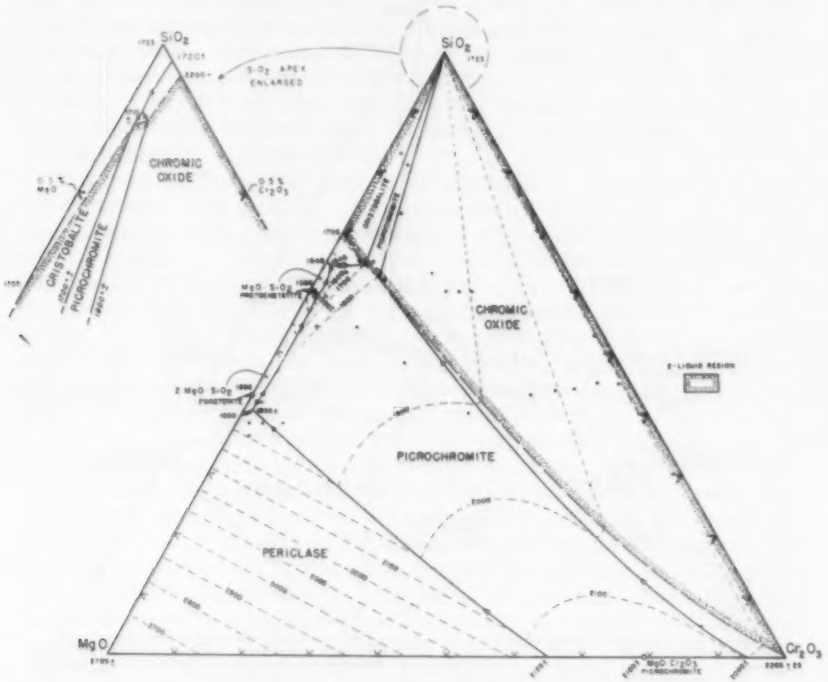


FIG. 51. Phase diagram for the system MgO-Cr_2O_3-SiO_2 (Keith, 1954). Dashed lines are isotherms.

tems anorthite-forsterite-silica (1) and diopside-forsterite-anorthite (28) (Fig. 50), which in turn are parts of the quaternary system CaO-MgO-Al_2O_3-SiO_2. The high-alumina part of this has been investigated by DeVries and Osborn (7). In this system if equilibrium is maintained during cooling, spinel appears only as a temporary phase. It can accumulate only if removed by crystal settling. Bowen (4, p. 277–281) showed that spinel could also arise by reaction of sunken crystals of anorthite and olivine with hotter liquid in depth, but the mechanism is not applicable in the rocks presently under discussion, because olivine is absent, and the data indicate that plagioclase is a late product of crystallization of the Bushveld magma.

It seems obvious that relationships shown in the anorthite-diopside-silica and anorthite-forsterite-silica joins of the four-component system CaO-MgO-Al_2O_3-SiO_2 cannot be an adequate guide to crystallization in the seven-component system CaO-MgO-FeO-Fe_2O_3-Al_2O_3-Cr_2O_3-SiO_2 represented in the rocks of the Critical Zone of the Bushveld Complex. A hint of the inadequacies is given by data from other component ternary and quaternary sys-

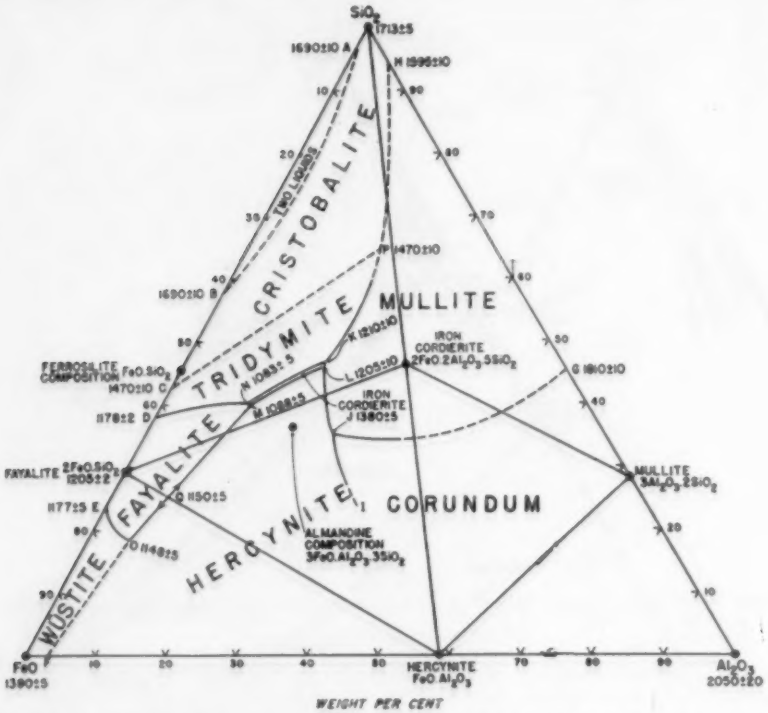


FIG. 52. Equilibrium diagram of the system FeO-Al_2O_3-SiO_2, showing fields of primary crystalline phases, tie lines, and invariant points (Schairer and Yagi, 34).

tems. In the system MgO-Cr_2O_3-SiO_2, Keith (21) has shown (Fig. 51) that from liquids of appropriate composition, picrochromite, protoenstatite and cristobalite crystallize together at a ternary eutectic (1546° C). This is the only pertinent system involving Cr_2O_3 for which data are presently available. However, other systems have a bearing on the problem. In the system FeO-Al_2O_3-SiO_2 (Fig. 52), Schairer and Yagi (34) find that a near-terminal point of crystallization is an invariant point (at about 1,088° C) involving iron cordierite, hercynite and fayalite. The composition of the

liquid at this point is FeO 47.7 percent, Al_2O_3 12.6 percent, SiO_2 39.7 percent. Yoder found (45, p. 586) that spinel can be formed in the presence of excess water vapor at much lower temperatures than in dry systems. Further speculation along this line, however, is fruitless in the face of ignorance of water vapor content and solubilities in the Bushveld magma at the time the chromitites were forming.

From these data, however, there are a few definite suggestions. One is that when iron or chromium is present in substantial amounts, a spinellid phase is not necessarily destroyed by reaction with liquid in the later stages of crystallization. The second is that iron-rich spinels would be soluble in certain silica-bearing liquids in substantial amounts. The third is that temperatures of liquids from which spinellids may crystallize have a lower limit that is considerably below the lower limits in the systems anorthite-forsterite-silica and diopside-forsterite-anorthite.

Returning to the specific problem of resolution of chromite at the time the chromitites were forming, it is presumed that in the upper part of the magma chamber both bronzite and chromite were crystallizing, and that the ratio of bronzite to chromite was high. Implicit in this assumption is that the solubility of Cr_2O_3 in the magma was low, hence that conditions were of the general kind obtaining along the protoenstatite-picrochromite boundary in Fig. 51. When, during formation of the pyroxenites, bronzite and chromite settled together to the floor of the complex, partial reversal of the previous process of crystallization is all that could be expected through reaction of settled crystals and supernatant liquid, or, after burial, by reaction of settled crystals and interstitial liquid. Throughout these stages, the liquids available for reaction would be characterized particularly by relatively high Mg : Fe ratios. If now the stage of chromitite accumulation is reached, the liquid in contact with settled chromite at the instant of settling is the same as before, but once the crystals are buried, and effective contact with supernatant liquid no longer exists, a new chemical system is brought into being. Settled crystals available for reaction are now almost all chromite. Reversal of the high-level course of crystallization is impossible; by reaction with chromite the interstitial liquid will be enriched in FeO and Al_2O_3 relative to MgO. The result may be a lowering of the freezing point of the liquid, and if the composition of the liquid moves across a phase boundary in the system or across a maximum of the liquidus, substantial solution of chromite may be possible.

The above may be dismissed as speculation without value, but the reasoning employed is certainly as valid as that by which the systems anorthite-diopside-silica and diopside-forsterite-anorthite have been applied to the crystallization of chromite, the major constituents of which do not even appear in these systems, and it has the advantage of being consistent with the petrographic evidence.

In connection with the problem of the chromitites, it is worth noting finally that some of the textural relations between bronzite and chromite, chain structure especially, could conceivably result from breakdown of a solid solu-

tion or of an intermediate compound. Neither is indicated by existing mineralogical or physico-chemical data, but they cannot yet be dismissed as possibilities.

Possible Role of Diffusion.—Partial resolution of settled crystals seems required by evidence that a Cr-enriched liquid was present during formation of the middle member, but the degree of enrichment required might be greatly diminished if the supply of chromite constituents to the sites of crystal growth were augmented by diffusion. Hess (20) has pointed out that cooling of a lopolithic mass would proceed under the influence of two cooling gradients, one with respect to the roof, one with respect to the floor. He suggests that the interplay of these two gradients, through its influence on diffusion, might have a bearing on the development of monomineralic rocks of the Stillwater Complex. Hess assumes, again, that the crystals of chromite and pyroxene accumulating on the floor were precipitated higher up in the magma chamber in response to cooling of the magma mainly from the top downward. Temperatures would in general rise from the top of the chamber downward, then fall off again downward from the interface between the magma and mass of settled crystals.

Now suppose crystallization of the middle member of the main chromite seam has begun. Chromite crystals settle to the floor and form a mass of crystals with interstitial liquid. This liquid is hotter than that in which chromite crystals precipitated and should be unsaturated with chromite. Partial resorption of chromite takes place. The interstitial liquid will thereby be cooled, but if, as seems probable, it was initially on the pyroxene side of the chromite-pyroxene boundary (Fig. 51), the first result of resorption will be to lower the freezing point of the liquid, which will favor further resorption. At a low concentration of Cr_2O_3 (probably at no more than 5 to 10%), however, the liquid will reach a composition corresponding to a point on the boundary or pass over to the chromite side. Further resorption of chromite will then increase the freezing temperature of the liquid. At some point the liquid will become saturated with chromite and resorption will stop. Eventually, the effect of loss of heat through the floor will be felt and cooling of the layer and interstitial liquid will begin. If the liquid has passed over to the Cr_2O_3 side of the phase boundary, chromite will precipitate out first. In the meanwhile, however, chromite is accumulating above the initial layer and the same process of resorption to the saturation point of the interstitial liquid is taking place. Before reprecipitation of chromite at this horizon can take place, however, crystallization of the original layer has begun. The interstitial liquid in the original layer is now depleted of Cr_2O_3, and a concentration gradient between the interstitial liquid here and that in the layer above is set up. Diffusion of chromium to the original layer takes place, and the layer is enriched in chromite. Interstitial liquid is at the same time displaced by growth of chromite crystals.

The process must end in the original layer shortly after the chromite-pyroxene peritectic is reached as the temperature falls. At this point simultaneous crystallization of pyroxene and chromite begins, yielding chains of

chromite poikilitically enclosed in pyroxene. These make room for themselves by pushing aside the surrounding chromite crystals.

The important aspect of the process described above is that it could lead to crystallization of a substantial amount of chromite and pyroxene in place, yet at no time would any very high concentration of Cr or Fe exist in the liquid, nor need there be any high percentage of liquid in the mush.

Upper Member of the Steelpoort Seam.—The upper member of the Steelpoort Seam shows a reversal of the changes observed in the transition from underlying pyroxenite through the lower member to the middle member of the seam. The content of pyroxene increases rapidly upward. Chain chromite in pyroxene disappears within a half inch of the base of the upper member. The textural relations show a progressive change upward that is the reverse of the upward change in the lower member.

Leader Seam.—Save that the lower contact of the Leader Seam is sharp to abruptly gradational, the features of the seam are similar to those described above for the Steelpoort Seam and explainable in the same terms.

The Hypothesis of Liquid Immiscibility.—The hypothesis of liquid immiscibility now requires further consideration in the light of the features of the lower, middle, and upper members of the Steelpoort Seam. The ratio of chromite to other minerals increases upward in the lower member, and we must account for this in terms of separation of a heavier liquid rich in Cr and Fe and either a silicate liquid or a silicate liquid containing settled crystals of bronzite. The heavier liquid must accumulate above, and the lighter silicate liquid must accumulate below. The writers are able to suppose only one set of circumstances that might lead to such a reversal of the positions expectable from relative specific gravities. Let us suppose that the accumulation of the pyroxenite underlying the lower member of the Steelpoort Seam is just complete. Due to abstraction of bronzite the superjacent magma is enriched in the constituents of chromite and plagioclase, and this change in composition results in liquid immiscibility. At the level represented by the lower member, resolution of settled chromite crystals might contribute to immiscibility. Separation of a Cr and Fe-rich liquid begins. The liquid is heavy, and globules of it forming in the magma settle downward to the floor, coming in contact with the pyroxenite. The pyroxenite is still a mush of crystals and interstitial plagioclase-rich liquid. This mush, being lighter, tends to be displaced by downward trickling of the heavy liquid above, the mechanism being analogous to the process of late gravitative liquid accumulation suggested by Hall and Bateman for the titaniferous magnetites of the Bushveld. Bronzite crystals ultimately become detached from the upper part of the pyroxenite and rise upward through the lower member of the Steelpoort Seam, some finally reaching the level of the top of the lower member.

The middle member of the Steelpoort Seam we may suppose to be purified by upward gravitative displacement of the silicate liquid phase, and we are now left only with the problem of accounting for the upper member of the Steelpoort Seam and its gradual upward passage into chromiferous pyroxenite above. We must now assume that the bronzite crystals of the upper mem-

ber represent crystals accumulated above the middle member of the seam during its purification. If all the above is granted, however, we still have a difficult question to answer, namely—What stops the accumulation of the Cr and Fe-rich liquid, and what causes accumulation of another layer of the liquid (Leader Seam) after only a few feet of chromiferous pyroxenite have accumulated? The only suggestion the authors can make is that slackening of magmatic currents, leading to rapid settling of bronzite crystals, causes liquid accumulation to be arrested and that quickening of the currents, with reduction in the rate of settling of bronzite, allows liquid accumulation to be resumed.

The neatness required of the mechanism outlined above strains credulity. Quite apart from this, however, it ignores the progressive nature of separation of two immiscible liquids when separation is a consequence of cooling. As pointed out long ago by Bowen (4, p. 7–10) unmixing is progressive and separation of globules of one liquid in another should continue until arrested by crystallization. Complete purification of a layer of an immiscible heavy liquid is virtually impossible; in the present case there should be definite indications of the silicate-rich liquid phase in the chromitite. None are present; in fact, there is nothing in the textural features of the chromitites and associated rocks to indicate immiscibility. A final difficulty is the distribution of the pyroxenite inclusions in the Steelpoort Seam. If the relative purity of the seam is due to upward displacement of pyroxene crystals in the Cr, Fe-rich liquid, why are pyroxenite inclusions found from top to bottom of the middle member, and how are we to account for the pyroxenite inclusions in the upper and lower members?

The difficulties cited make the hypothesis of liquid immiscibility unattractive. This conclusion is consistent with experimental evidence from relevant systems. Keith's phase diagram (Fig. 51) shows liquid immiscibility in the system MgO-SiO_2-Cr_2O_3 only at high values of the ratio $SiO_2 + Cr_2O_3 : MgO$; the attainment of such ratios in magmatic systems is questionable. Phase diagrams involving other spinels discourage the idea that liquid immiscibility is operative in noritic magmas. Again, however, the phase diagrams can hardly be considered an adequate guide.

In marked contrast to equilibrium studies are experiments cited by R. Fischer (12). Fischer states that melts made from mixtures of normal gabbro with 2.5, 5, and 10 percent chromite all showed separation into a Cr-rich liquid and a Cr-poor liquid at 1,400° C. He states further that crystallization of the Cr-rich liquid yielded chromite and olivine. Fischer's account is very brief, the evidence given is inconclusive, and the applicability of his findings to the Bushveld Complex is difficult to assess. For the present, it seems impossible to accept liquid immiscibility as a principal mechanism of formation. However, liquid immiscibilty and magmatic sedimentation plus partial resolution are not necessarily mutually exclusive. The possible results of a combination of settling of pyroxene and chromite, resolution, separation of a chrome-rich liquid, and operation of magmatic currents are not readily assessed solely in terms of textural and structural criteria, and physical chemistry must provide final corroboration of any genetic hypothesis.

SUMMARY AND CONCLUSIONS

Field and laboratory evidence point to the following conclusions regarding the origin of the Steelpoort and Leader chromitite seams in the pyroxenite series of the eastern part of the Bushveld Complex:

1. The chromitite seams are a consequence of magmatic differentiation. Available evidence is against formation by selective metasomatism of pre-existing sedimentary rocks.

2. Structural features of the chromitites and associated rocks indicate that magmatic currents played an important part in the development of contrasting rock types, producing differential deposition of crystals settling through the magma.

3. Textural features of the pyroxenites associated with the chromitites are consistent with (1) settling and early crystallization of chromite and bronzite, (2) crystallization of interstitial liquid to yield overgrowths on the settled crystals and interstitial plagioclase.

4. Biotite and clinopyroxene are end-stage magmatic products. Their crystallization was unrelated to the formation of chomite.

5. The order of crystallization of minerals in the pyroxenites, in the upper and lower members of the Steelpoort Seam, and in the basal transition and upper member of the Leader Seam indicates that the chromitite seams did not form by residual liquid accumulation.

6. Textural and compositional features of the chromitites are consistent with the hypothesis that the main accumulation of chromite and bronzite was accomplished by magmatic sedimentation, but they indicate that part of the chromite and bronzite crystallized in situ. Partial resolution of settled crystals seems required as a supplementary process. Diffusion related to thermal gradients may have contributed to enrichment in chromite.

7. Formation of the chromitite seams partly or wholly as a conseqeuce of liquid immiscibility offers formidable difficulties, but liquid immiscibility may conceivably have played a supplementary role in chromitite formation.

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Jan. 16, 1959

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STRUCTURE AND ROCK ALTERATION AT THE ELIZABETH MINE, VERMONT

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PART I

STRUCTURE AT THE ELIZABETH MINE

ABSTRACT

The Elizabeth copper mine in east-central Vermont is a concordant orebody lying within medium to high-grade metamorphic rocks of the Gile Mountain formation, believed to be Ordovician in age.

The major structural features of the district are the east-dipping eastern limb of the Green Mountain anticlinorium, and the Strafford dome, which is marked by the development of an abnormal "Christmas-tree" pattern of minor folds. Due to a flat northerly plunge, the easterly part of this structure crops out as a series of recumbent dextral folds in which the older rocks appear on the inside of the northerly-plunging V structures. Minor sinistral folds and flexures are common in the area, and both pre- and post-date the dextral folds associated with the Strafford dome.

The Elizabeth orebodies are bedded within the rock sequence at the contact of amphibolite and mica schists and are structurally related to the "Christmas-tree" pattern of folds. The ore is localized in fold positions and on straight limbs between fold positions. Schist breccia within the ore, ore infilling the space between parted bedding planes in drag fold positions, and veins filled with ore suggest that the ore was introduced into permeable zones formed during deformation and dated as middle and/or late Devonian (Acadian). It is believed that the major ore control in the district was the crushed and folded contact of thick competent amphibolite beds with incompetent schists interbedded with quartzites.

INTRODUCTION

THE Elizabeth copper mine is located in the Strafford quadrangle in central Vermont, 2 miles southeast of the village of South Strafford (Fig. 1). It is one of a group of copper deposits in the Orange County copper district of Vermont. Mines and prospects in this district are illustrated in Figure 1. The deposits are confined to the Gile Mountain formation, the Standing Pond member of the Waits River formation, and the non-calcareous schist phases of the Waits River formation. In all cases, the deposits are close to amphibolite beds.

All known copper deposits in Vermont together with gold and lead mines and propects are recorded on Figure 2. The contour outlining the gold deposits corresponds to the kyanite and staurolite metamorphic zones and accompanying intrusive rocks of Vermont. The copper and lead deposits lie to the east and west of the gold contour lines, and the distribution suggests a

temperature zoning. In the Strafford quadrangle, lead forms the outermost zone, and the copper is intermediate between the gold and the lead. The accessory sphalerite of the Elizabeth copper mine is black and high in iron content, but the sphalerite in the lead deposits is yellow and low in iron

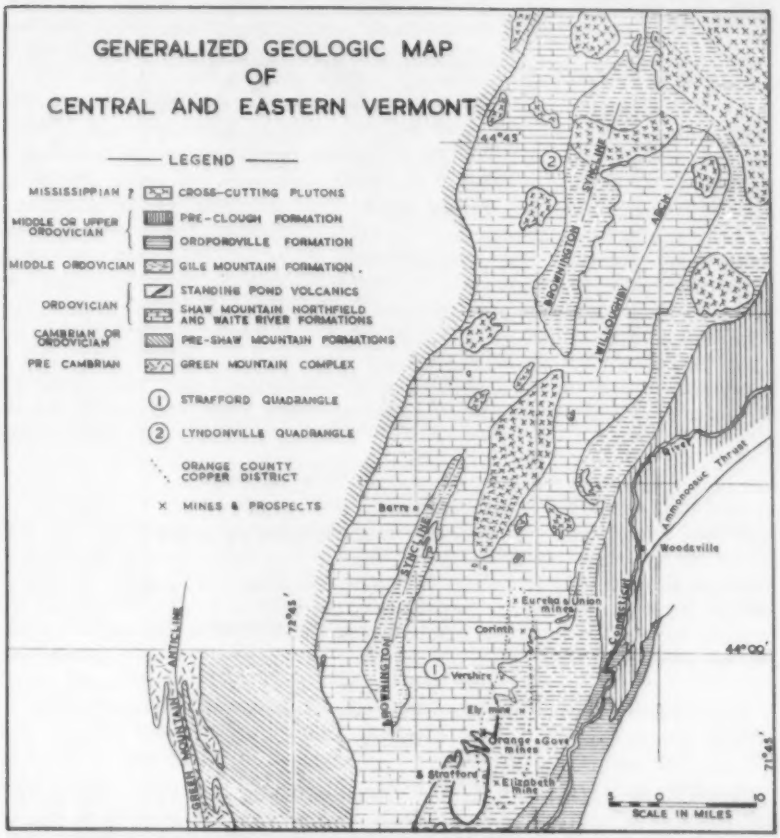

FIG. 1. Regional geologic map showing the location of the Orange County Copper District. (After maps of Thompson and Dennis and others.)

content, and indicates that the metal distribution is a true temperature zoning.

History and Production.—The deposits of the Orange County copper district were discovered after the American Revolution and were the chief source of American copper production until the exploitation of the Michigan copper deposits starting around 1846.

The Elizabeth mine, found in 1793, is listed as the earliest discovered deposit. The Ely mine was worked from 1821 onwards and Pike Hill from 1854. Most of the deposits are of low grade, and none have been operated continuously for any great length of time. As copper prices fluctuated, interest renewed and waned and only the Elizabeth mine has been operated since World War I.

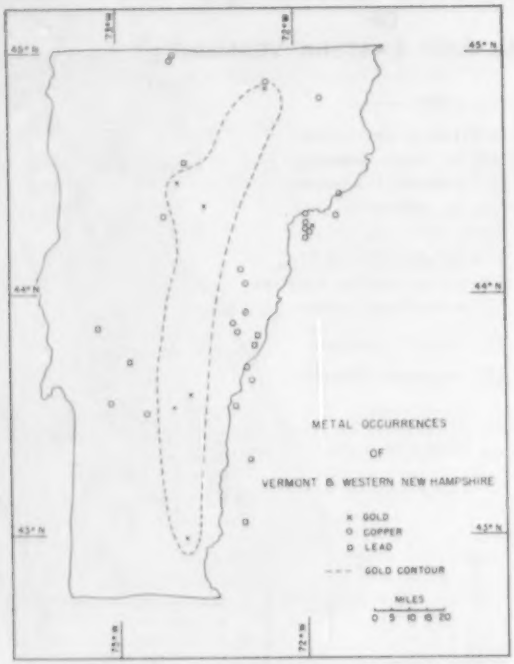

FIG. 2.

Initially the Elizabeth mine was operated for its pyrrhotite used in the manufacture of iron sulfate (copperas), and it was not until 1830 that a company was formed to exploit the deposit for its copper content. The estimated production [1] of the mines prior to 1943 is:

Mine	Tons of ore mined	Average grade	Pounds of copper
Elizabeth	250,000	2.2	10,500,000
Ely	500,000	3.5	35,000,000
Eureka } Pike Hill	60,000	2.5	3,000,000
Union } Pike Hill	90,000?	?	5,600,000
	900,000		54,100,000

[1] White and Eric (1944, p. 7).

These production figures do not include the smaller mines for which there are no recorded data.

The Elizabeth mine was reopened in 1943 by the Vermont Copper Company under the sponsorship of George Adams Ellis of Bennington and Stanley Wilson, a former governor of Vermont. Since 1954, the mine has been operated by Appalachian Sulphides Incorporated, a wholly owned subsidiary of the Nipissing Mines Company Limited, of Canada.

The total production from 1943 to the closing of the mine in February 1958 was 2,967,000 tons of ore averaging 1.706% Cu and containing 100,915,000 lb of copper of which 91,495,800 lb or 90.67% was recovered into concentrate having an average content of 24.06% Cu. The highest average grade ore of any one year since 1943 was 2.56% Cu in 1946. The highest production of ore and recovered copper in any one year since 1943 was 294,396 tons of ore averaging 1.65% Cu and yielding 8,774,339 pounds of copper in 1955. Zinc and silver were recovered from the copper concentrate and averaged 0.5% Zn and 0.1 ounce of silver per ton. The concentrate was shipped to the Phelps-Dodge refinery on Long Island, New York. The mill handled 800 tons per day under normal operating conditions although it has been capable of handling peak production of 1,100 tons per day. Pyrrhotite has been concentrated since 1952 and sold to Brown Company, Berlin, New Hampshire where sulfur is recovered for the production of sulfuric acid.

STRATIGRAPHY

General.—The orebodies of the Elizabeth mine lie within the Gile Mountain formation, which is underlain immediately to the west by the Standing Pond amphibolite member of the Waits River formation and the Waits River formation itself. The regional structure discussed in this paper is outlined by the Standing Pond amphibolite and, where this member is absent, by the contact of the Gile Mountain and Waits River formations. These formations are part of a thick homoclinal sequence of Paleozoic rocks lying between the Green Mountains and the Connecticut River (Fig. 1).

Gile Mountain Formation.—The Gile Mountain formation crops out in a belt 3½ to 9 miles wide extending northerly through the central and eastern portions of the Strafford quadrangle. The formation is bounded on the west by the calcareous rocks of the Waits River formation, and on the east by the Orfordville formation. The lithologic character of the beds of the Gile Mountain formation described here is principally that of the rocks in the vicinity of the Elizabeth mine.

The Gile Mountain formation is essentially a noncalcareous formation consisting of gray to dark mica schist, gray to light gray micaceous quartzites, thin impure quartzite bands, and scattered, weakly calcareous horizons. Beds of limestone are rare, and, where found, are generally less than one foot in thickness. Phyllites are absent in the vicinity of the mine but become increasingly evident to the east where the degree of metamorphism lessens.

The light to dark mica schist is generally a muscovite-biotite-garnet schist in which kyanite is commonly developed and staurolite to a lesser extent.

Schists in which biotite predominates over muscovite are rare; the dark color of the schists is due to varying amounts of finely divided, disseminated carbonaceous material.[2] Under a microscope, the muscovite of some schists is almost opaque due to the preponderance of carbonaceous matter. Isolated lenses of the black material one-half inch thick and several feet long are noted in the underground workings of the Elizabeth mine. As the schists grade into more arenaceous facies, the amount of carbonaceous material becomes less, and the rock becomes lighter in color.

Field observations indicate that light gray quartzitic schist and dark schist are developed in roughly equal proportions. The two types grade into each other, and the lithologic character of a bed is generally not maintained for more than a few feet in thickness. The maximum thickness of a bed of uniform nature is approximately thirty feet.

Quartzites and impure quartzites are lenticular in nature and can seldom be traced through a fan of diamond drill holes, even where individual holes are ten or twenty feet apart, and the horizons are known to pass through successive holes. Both underground and field observations indicate that the lenticular nature of the beds is predominantly a depositional characteristic of the original sediments. Biotite-tremolite schist is present in discontinuous beds within the ore zone of the Elizabeth mine. The rock consists of pale biotite, tremolite, and lesser amounts of calcite and andesine. The rock, which was named "skarn" by Mikkola, grades into dark biotite schist and amphibolite both along and across the strike of the bed.

Fifteen stratigraphically distinct beds of medium- to coarse-grained amphibolite occur in the lower part of the Gile Mountain formation and are marked on the surface map, Figure 3, as beds A to M. Some bands are locally developed and discontinuous; however, many of them can be traced four to five miles, and several have been traced twelve miles. The greatest thickness of any bed is 200 feet. Field and underground observations show that the beds lens out both along strike and down dip, and that the variation in thickness of a specific bed is generally unrelated to folding. However, tectonic thinning and thickening does occur in the Standing Pond amphibolite in the vicinity of the village of Strafford (Fig. 3) and to a lesser degree underground in the Westwall amphibolite (Fig. 15).

The term "amphibolite" is used here to designate rocks that are rich in black or dark green amphibole which has the refractive indices of common hornblende. Although used, the term is not always strictly applicable as the beds may contain as little as eight percent hornblende whereas the bulk of the rock is composed of plagioclase (An 17–38) and calcite. Varying proportions of minerals permit amphibolite bands to be divided into submembers that differ greatly in macroscopic appearance.

The common amphibolite is medium-grained and distinctly gneissic. Fine-grained epidote or zoisite (.02 to 1.0 mm in diameter) is locally abundant. Pale biotite is commonly present and red almandite garnet (3 to 9 mm in diameter) is sporadically developed. Accessory minerals may include

[2] As distinct from graphite.

magnetite, ilmenite, rutile, apatite, zircon, and sphene. Quartz is a minor constituent and may be absent. The hornblende is generally unoriented and the laths (4 to 10 mm in length) have grown in random directions athwart the gneissosity. Accessory minerals, largely confined to the gneissic bands

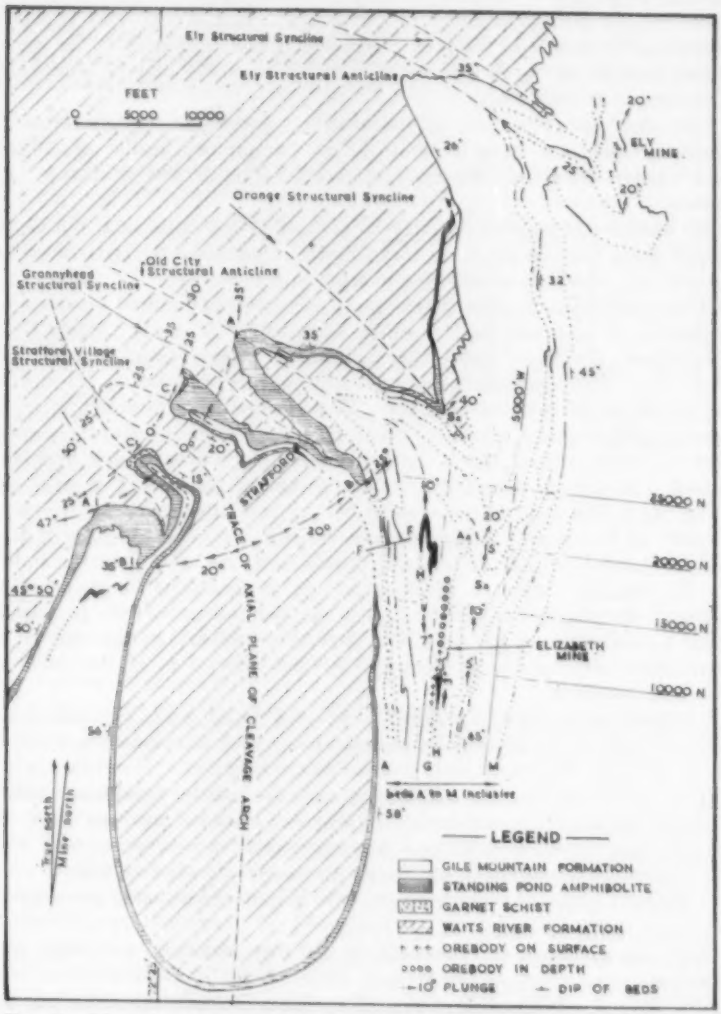

FIG. 3. Map showing the principal geologic features in the vicinity of the mine (Data after White, Doll, Stoiber, Mikkola, Dwelley and the author). Mine Coordinates shown.

rich in plagioclase, in places form distinct lines of minerals that pass uninterrupted through hornblende laths. In some instances, lines of accessory minerals may be rotated by the hornblende as much as fifteen degrees.

In coarse-grained amphibolite, hornblende laths are larger and are either stubby or in groups of elongate clusters (rosettes) in which individual hornblende crystals are up to six inches in length. Hornblende may constitute as much as 50 percent of the rock. Banding is not as evident in the coarse-grained amphibolites as in the medium-grained ones and may be absent over thicknesses of several feet.

One other distinct variety of amphibolite is present in the Gile Mountain formation, namely, a characteristically dark fine-grained needle amphibolite, which closely resembles the common amphibolite of the Standing Pond member.

All varieties of amphibolite may be present in one band, and the contact between them may be sharp or transitional. Discontinuous beds of impure quartzite and schist are interbedded in such sequences.

Alteration zones of garnetiferous mica schist, called "altered amphibolite," are present as lenticular bands within amphibolite in places. Black biotite is abundantly developed within this rock and is largely pseudomorphic after hornblende. Red almandine garnets range in size from 2 to 70 mm but average 15 to 25 mm in diameter. Fine-grained tan staurolite is locally abundant and attains a maximum observed size of 1 mm in diameter. Muscovite is always present, and in some specimens is the predominant mineral of the rock. As the percentage of muscovite increases, the amount of plagioclase and calcite in the rock decreases until both of the latter minerals may be an accessory or be absent. Magnetite and ilmenite are generally present while scattered pyrrhotite and occasionally chalcopyrite are also present. Sphene may be abundant. Quartz which is present as disseminated grains in the matrix of the plagioclase groundmass is no more common than it is in the typical amphibolites of the district. However, contrary to the case in the amphibolites, clear quartz is present in bedded lenses 5 to 15 mm wide and up to one foot long.

"Altered amphibolite" is widely developed throughout Vermont and is associated with the Standing Pond amphibolite and accompanying amphibolites of the Gile Mountain and Waits River formations. However, only in the rock in the vicinity of the Elizabeth mine are sulfides known to make up a substantial portion of the rock. Assays and chemical analysis show that the total iron content may attain a maximum of 18 weight percent, of which 9 to 12 percent is present in pyrrhotite and accessory chalcopyrite.

Estimated modes of rocks from the Gile Mountain formation are presented in Table 1.

Doll has estimated the thickness of the Gile Mountain formation to be 6,500 feet.

Standing Pond Member of the Waits River Formation.—The Standing Pond amphibolite forms the boundary between the Waits River and the Gile Mountain formations throughout a large part of Vermont.

The rocks of the member consist of very fine-grained needle amphibolite, together with lesser amounts of coarse hornblende schist and medium-grained gneissic amphibolite similar to some amphibolite beds of the Gile Mountain formation. Locally, the amphibolite beds grade into dense black biotite and biotite-tremolite schist. The thickness of the Standing Pond amphibolite varies from zero to 1,000 feet, but much of this variation is due to tectonic thickening and thinning. The thickness of the unit away from highly deformed areas appears to range between 100 and 200 feet.

TABLE 1

ESTIMATED MODES OF ROCKS FROM THE GILE MOUNTAIN FORMATION

Rock EZ	3	7	568	318	316	287	228	11	294	320	317	9	A18	276	314
Quartz	67	63	10	13	1		1		26	1	1	3	2	18	2
Oligoclase	11	13		27	4	67					20			25	
Andesine			25					6	19	34		40		22	39
Calcite	Tr	Tr				Tr	9	22	21	9	5	31	26		
Muscovite	2	1	19	8	24				8						
Sericite							5						6	34	3
Biotite	13	5	28	33	43	Tr	4	46	22	1	1	Tr	6	35	17
Chlorite	3	2					Tr	Tr	Tr	2	1		6		
Hornblende									Tr	50	71	15	26		
Actinolite		11				30	34	16							
Clinozoisite									1	2	Tr	8	19		
Garnet	2	5	1	7	Tr				Tr						
Staurolite				Tr											9
Kyanite				3	9										
Apatite	Tr	Tr		Tr			Tr			Tr			Tr	Tr	
Zircon			Tr	Tr	Tr										
Tourmaline				Tr											
Sphene								1		Tr					
Rutile	1						1			1			Tr		
Ilmenite										Tr			3		
Magnetite	Tr	1	2	2	Tr				3		2	2		4	1
Sulphide						3	5	9						1	
Carbon			14	7	18										

EZ 3, 7 Impure quartzite; EZ 568, 318, 316 biotite-kyanite schist; EZ 287, 228 feldspar rock; EZ 11 biotite-tremolite schist, "skarn"; EZ 294 biotite schist; EZ 320, 317, 9, A18 amphibolite; EZ 276, 314 schists from Stage 1 alteration zone within amphibolite.

The constituent minerals of the amphibolites are the same as those of the Gile Mountain amphibolites and have similar ranges of compositional variation. The proportion of ferromagnesian content tends to be higher in the needle amphibolite than in the other types, and small lentils of quartz up to one foot long are common.

Field observations by J. B. Thompson in the vicinity of Springfield, Vermont, show that the Standing Pond amphibolite in the chlorite zone is composed of finely-layered chlorite schist containing angular fragments of feldspar, indicating a tuffaceous origin. Transitional zones between the various types of amphibolites of the Gile Mountain formation suggest original variations in bulk composition, which would be adequately explained if the amphibolites were of a tuffaceous origin. If the amphibolites were originally tuffs,

considerable water sorting and contamination by extraneous detritus must have taken place to account for the variations which exist.

Waits River Formation.—In the vicinity of the mine, the Waits River formation consists of a series of interbedded impure limestones, calcareous mica schists, mica schist, quartzitic mica schist and impure quartzites. Farther afield from the mine area, where the rocks are less metamorphosed, phyllites are present.

Individual beds of the formation are from inches to 30 to 40 feet thick, but are most commonly 2 to 10 feet thick. The various lithologic types occur in distinct beds but also grade into each other. Massive calcareous beds range from blue-gray to a lighter color and grade from limestone to arenaceous limestones to calcareous sandstones. The interbedded gray to dark gray schists, quartzitic schists and impure quartzites show a marked increase in number towards the western contact of the Gile Mountain formation. In many places in this zone, random outcrops appear in no way different in lithologic character to outcrops within the Gile Mountain formation.

Age of the Formations.—The Waits River formation is generally considered to be of Ordovician age and older than the Gile Mountain formation which is of middle Ordovician or early Devonian age. A full analysis of the problem is dealt with by Doll, White and Jahns, and Lyons.

METAMORPHISM

The highest metamorphic grade attained in the area is that of the sillimanite zone. However, sillimanite is localized and rare compared to kyanite, suggesting that the rocks of the Strafford dome and the staurolite-kyanite rocks as far east as the Elizabeth mine were heated to temperatures close to the inversion temperature of kyanite-sillimanite; where this temperature was exceeded locally, sillimanite-bearing rocks were developed.

Staurolite is widely developed, but like sillimanite, is comparatively rare compared to kyanite and its common assemblage is biotite-muscovite-garnet-staurolite.

The only isograd map of the Strafford quadrangle is a small scale map of 20 miles to the inch compiled by J. B. Thompson (Plate 3). The isograds have a concentric distribution in relation to the position of the Strafford dome, and it is significant that the intensity of metamorphic grade and degree of structural deformation decrease to the east and west away from the center of the dome. A gravity study by Bean suggests that a rock, with a specific gravity approximately that of a granite, is present beneath the dome.

Appreciable amounts of chlorite and fine-grained muscovite are present in some high-grade metamorphic rocks but are not thought to represent disequilibrium conditions under increasing temperature conditions. These assemblages are most marked in the vicinity of the Elizabeth mine and, for the most part, are believed to be retrograde products of metamorphic minerals that resulted from hydrothermal activity after the thermal peak of metamorphism.

Four distinct types of alteration are recognized on the basis of mineralogy

alone and also on zonal distribution in relation to the Elizabeth orebodies. The writer believes that the first three types are part of a continuous cycle of alteration, which, together with the fourth type, may be categorized into chronological stages. The metamorphic index minerals, kyanite, hornblende, garnet, and biotite are pseudomorphically replaced by hydrous minerals in the alteration zones of each stage, and they indicate that alteration occurred after the thermal peak of metamorphism. The appearance of second-generation garnets beside and across the sites of pseudomorphs after earlier garnets demonstrates that alteration was short-lived and that metamorphism of the alteration zones with decreasing temperature produced a second generation of garnets following the thermal peak of metamorphism. The metamorphic index minerals formed in the alteration zones under decreasing temperature conditions include staurolite, garnet, biotite, and chlorite.

That second-generation garnets are strongly rotated indicates that alteration and metamorphism of the alteration zone occurred under decreasing temperature conditions during deformation. In contrast, the garnets formed during progressive metamorphism show little rotational effect. Hornblende shows a strong bedding lineation where the amphibolite containing the hornblende is fine grained and non-gneissic. In such instances the lineation remains in the plane of bedding even in the apical positions of folds. Where the amphibolite is coarse grained and gneissic, hornblende has a random orientation. These data demonstrate that the thermal peak of metamorphism occurred largely before the major deformation of the area, and that alteration occurred with decreasing temperature that overlapped the period of deformation that formed the major structural features of the area. S-shaped trains of mineral inclusions in a limited number of garnets and hornblende grains in rocks not associated with alteration zones indicate that some overlapping of the thermal and deformation periods occurred.

The various types of alteration mentioned above are categorized into chronological stages by the presence of different metamorphic index minerals in the alteration zones. The first stage, although represented in the mine, has no zonal relationship to the orebodies. It is confined to zones that are now represented by coarse-grained garnet-biotite-muscovite-staurolite schist widely developed within the Standing Pond amphibolite and in associated amphibolites throughout most of Vermont. This altered rock in places shows a striking resemblance to amphibolite, and differs only in the presence of black biotite pseudomorphic after hornblende. Where alteration is more advanced, white mica replaces plagioclase along the frayed and ragged edges of plagioclase grains and also forms as unit pseudomorphs after biotite. The mineralogic features observed are consistent with reaction between solutions and amphibolite. The writer believes that the alteration period was short-lived in comparison to the metamorphic cycle, as metamorphism of the alteration zone formed staurolite and garnet.

The second stage of alteration is associated with the Elizabeth orebodies. As in the first stage, hornblende is pseudomorphically replaced by biotite. Plagioclase is replaced by sericite along grain boundaries, and kyanite is pseudomorphically replaced by muscovite. Garnet of the Gile Mountain

schists is pseudomorphically replaced by biotite, which, immediately against the ore, is in turn replaced by very fine grained pyrrhotite and quartz. Second-generation garnets are developed beside such pseudomorphs and in places have grown partly across their sites.

The third stage of alteration believed by the writer to be the end phase of the hydrothermal activity that gave rise to the Elizabeth orebody, is always in well-defined bleach zones as far as 500 feet away from the ore zone. It also includes some minor modifications to the alteration zone about the Elizabeth orebodies, notably the pseudomorphic replacement of biotite by chlorite (pennine). The stage is characterized by the abundant development of pennine after hornblende, garnet, and biotite. The abundant development of pennine suggests that alteration occurred during temperature and pressure conditions equivalent to the chlorite zone of metamorphism.

The fourth stage of alteration appears to have taken place on a regional scale and post-dates Mississippian (?) diabase dikes of the area, the minerals of which are also altered. Minor amounts of chlorite are developed after hornblende, garnet, and biotite but are neither confined to zones nor accompanied by bleaching of the rocks as are the preceding stages. The dikes are cut by post-Mississippian (?) faults, and it is possible that these faults belong to a period of comparatively weak deformation that gave rise to the fourth stage of alteration.

The first three stages will be discussed in detail in Part II of this paper.

IGNEOUS ROCKS

Diabase rocks occur in the vicinity of the mine. The dikes strike approximately east-west and dip at angles close to 90 degrees. Two such dikes, exposed by underground development, intersect north-striking faults in the ore zone and in both instances the dike rock has been intruded locally along the fault. The dikes in turn are cut by post—dike faults as already mentioned. Titanium content of augite in the diabase suggests alkali affinities, and Fowler-Billings correlates the dikes with the White Mountain magma series, Mississippian (?) in age.

Exposures of granite plutons are abundant 16 miles north-northwest of the mine. The nearest exposure is small, and lies 8 miles to the northwest (Fig. 1).

QUARTZ VEINS

Quartz veins are common in all the metamorphic rocks of the area. They occur as bedding veins and lenses, irregular masses, and veins that cross the bedding of the rocks. Most commonly the quartz veins are short lenses (one to two feet long) and lie in the plane of bedding schistosity. Some of the veins are pegmatitic and contain minerals that are common to the surrounding schists. Minerals noted are coarse kyanite crystals, muscovite, biotite, garnet, calcite, zoisite, ilmenite, pyrrhotite, chalcopyrite, rutile, and a few large masses of tourmaline. Apart from quartz, not more than two of the above minerals generally occur together in any one vein.

Evidence such as concordance with the bedding schistosity, a few offsets by shears contemporaneously developed during folding, mineralogy compatible with the adjacent schists, and absence of the veins in slates of the chlorite zone suggests that these veins formed by metamorphic differentiation.

REGIONAL STRUCTURE

Introduction.—The rocks of central and eastern Vermont are part of a thick homoclinal sequence of metasediments and metavolcanics that form the eastern limb of the Green Mountain anticlinorium. Minor folds are normal for the eastern limb of an anticline except in the vicinity of the Strafford dome, and other domes to the south, where the dominant pattern is an abnormal "Christmas-tree" series of folds. Between the Elizabeth mine and the Ely mine, these abnormal folds and accompanying axial plane cleavage are deformed by flexures, the traces of the axial plane of which cut across the trace of the axial planes of the "Christmas-tree" folds at large angles. These flexures clearly post-date the "Christmas-tree" folds and it is proposed to call them *late-structure* folds. The folds mentioned above, which are normal for an eastern limb of a major anticline, will be called *early-structure* folds.

This terminology differs from that of White and Jahns, Dennis, and others whose late-structure folds correspond to the "Christmas-tree" folding. The latter authors do not name what have been called late-structure folds in this paper.

Early Structure.—As defined above, early-structure folds are those that are normal for the eastern limb of an anticline. Such folds, as observed in the vicinity of the Strafford dome, are all minor folds. However, it is likely, in my opinion, that the Brownington syncline and the Willoughby arch [3] (Fig. 1) form an early-structure fold in which the Willoughby arch has been considerably modified by later vertically acting forces, which gave rise to "Christmas-tree" folds. Taken at face value, the Brownington syncline and the Willoughby arch form a major fold that is normal for the eastern limb of the Green Mountain anticlinorium, and on all three flanks of this fold dragfolds exhibit a normal pattern. However, on the eastern limb of the Willoughby arch, and, to a lesser extent on its western flank, abnormal "Christmas-tree" folds are also present.

Excluding these abnormal folds, a diagrammatic east-west cross-section of the structure through the Lyndonville quadrangle and farther south in the vicinity of the Elizabeth mine would be of the general shape shown in Figure 4a.

Minor folds conforming to this interpretation are evident in the mine and its vicinity.

"Christmas-tree" Structure.—The overall trend of the Waits River and Gile Mountain formations is essentially parallel to the trend of the Orfordville and pre-Clough formations (Fig. 1). However, in detail, the mapped contact of the Waits River and Gile Mountain formations forms a dextral pat-

[3] Called the Danville anticline (Eric) farther south in the St. Johnsbury quadrangle.

tern of zig-zag folds plunging north-northeast. As the Gile Mountain formation is younger than the Waits River formation, the northeasterly plunging dextral pattern of folds is, therefore, opposite to that expected. This dextral pattern of folding is also reflected by amphibolite bands within the Gile Mountain formation. However, the amplitude of a given fold as outlined by successively more easterly amphibolite bands, decreases in an easterly direction until the structure of the Gile Mountain formation becomes a steeply dipping (60 to 80° E) series of metasediments exhibiting only minor drag folds (Fig. 3).

West of the mine, the dextral zig-zag folds give way to a large doubly plunging anticline known as the Strafford dome. This structure, as outlined by the Standing Pond member of the Waits River formation, is approximately eight miles long and three and one-half miles wide. As seen in Figure 3, the crestal line of the Strafford dome strikes approximately north. To the west of this line, the pattern of folds is predominantly sinistral and plunges south to west.

A study of the folds at the northern end of the Strafford dome illustrates the way in which the sinistral fold patterns west of the crestal line of the dome change to dextral patterns on the eastern side. The folds on the eastern side, shown in Figure 3, include the Grannyhand structural syncline[4] and the Strafford Village structural anticline. These folds are relatively open with the exception of the Strafford Village structural anticline, which is an attenuated isoclinal fold with a distinctive blunt nose. The plunge of these various folds and other minor folds ranges between 15 and 40 degrees and increases in the direction of the plunge to the north-north-east.

The group of folds on the western side of the crestal line of the Strafford dome plunges in the opposite direction to those on the eastern side at angles of 8 to 48 degrees, the angle of plunge increasing in a westerly to southwesterly direction away from the center of the Strafford dome. The shape of fold C_1 has much in common with the shape of the Strafford Village structural anticline inasmuch as both are isoclinal and are characterized by blunt noses, attenuated limbs, and a distinctive coarse garnet schist in the nose of both folds. These two folds are, in fact, one and the same fold, the axial plane of which is arched over the Strafford dome. The horizontal projection of the axis of fold CC_1 is indicated on Figure 3. Likewise the Grannyhand structural syncline and B_1 together with the Old City structural anticline and A_1 are similar pairs of folds wrapped about the dome structure.

Slip cleavage is highly developed in the area and always maintains an "axial plane" attitude to both the major and minor folds. The slip cleavage is almost entirely parallel to bedding within the Strafford dome as outlined by the Standing Pond member and can be seen only in fold positions, where it is apparent as an axial plane slip cleavage. Along the strike of the schists, away from fold positions, the cleavage merges with the plane of the bedding and can no longer be recognized. On the flanks of the dome, slip cleavage

[4] The term "structural syncline" has been previously suggested by McKinstry. In contrast to "stratigraphic syncline," it defines a fold whose limbs dip towards each other irrespective of the relative ages of the rocks.

dips away at flatter angles than the overall attitude of bedding but still maintains an axial plane attitude to folds. Thus cleavage forms an arch that is largely coincident in attitude with that of the sediments.

The features of the regional structure and the associated cleavage arch have been reconstructed in Figure 4b. This shows that the greater part of the fold development is confined to the eastern edge of the Waits River formation.

Data significant to this structural problem are the presence of a gravity low anomaly beneath the Strafford dome and a belt of maximum metamorphic intensity of the region, which is also coincident in position with the Strafford dome.

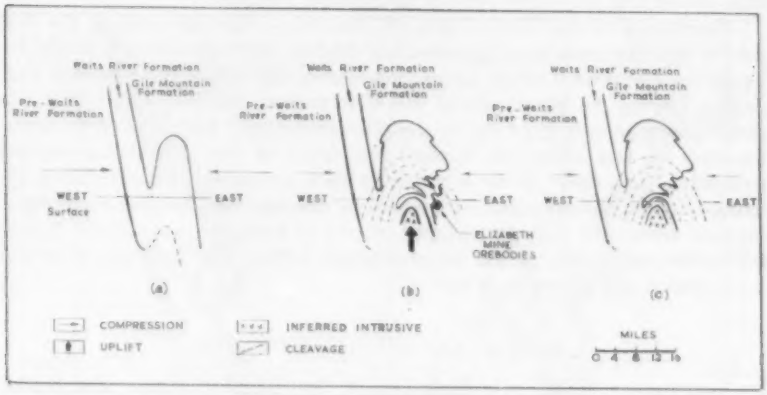

FIG. 4. Cross-sections showing the sequence of fold development in east-central Vermont. (a) Early-structure folding, (b) "Christmas-tree" folding, and (c) late-structure folding superimposed on main-structure.

In his discussion of a gravity study of the area, Bean states his belief that the gravity low is due to a mass of low density rock beneath the surface. Taking into account the low density of the core rocks of the Lebanon and Mascoma domes of western New Hampshire, together with those of the Chester dome to the southwest of the Strafford dome, Bean calculates the depth of the top of the anomalous mass of "gneiss" to be in the order of 2,500 feet.

The presence of such a mass of rock and development of a sillimanite zone of metamorphism above it on the surface suggests that the Strafford dome and related fold structures were produced by the upward movement of a high temperature mass of low density rock.

Late Structure.—Late structure is represented by the deformation of folds and accompanying cleavage formed during the "Christmas-tree" fold development. White and Eric delineated "cleavage rolls" (Plate 2) in which the cleavage strikes 20 to 70 degrees more westerly than the regional north-northwest trend. In the vicinity of the Ely mine, they show that the axes

of the flexures strike between N20°E and N25°E and plunge 23 degrees to N36°E. The flexures are of a regional nature and reach five miles in length. The trend of their axes and the degree of plunge are similar to those of the folds of the "Christmas-tree" structure; however, the traces of their axial planes cross the trace of the axial planes of the main-structure folds at angles as great as 60 degrees (Fig. 4c).

The overall fold pattern of the cleavage flexures is sinistral and similar in trend, trend of fold axes and plunges to the folds developed during the early-structure deformation (Fig. 4a). Both sets of folds are consistent with upward movement of rocks on the east with respect to those on the west. That is, both sets of folds are dragfolds on the east limb of a regional anticline whose axis lies to the west of east-central Vermont.

Correlation of the Three Types of Structure.—The inference of the field data is that the early and late structure folding was formed by a single deformation (Acadian), which formed the homoclinal structure of eastern Vermont. During the late stages of this deformation, localized uplift by a low density mass of rock gave rise to the "Christmas-tree" folds that were superimposed on, and effectively masked the detail of the pre-existing simpler structure. The uplift of the low density rock presumably ceased during the dying phase of compression, represented by cleavage and bedding rolls superimposed across the "Christmas-tree" pattern of folds but sympathetic in both fold sense and plunge to the early-structure folds. The sequence of events is illustrated in Figures 4a, b and c.

STRUCTURE AT THE ELIZABETH MINE

Introduction.—The two orebodies of the Elizabeth mine are bedded within the Gile Mountain formation at the contact of schist and two closely spaced amphibolite beds. The orebodies are structurally related to the "Christmas-tree" folds of the area (Fig. 4). Minor folds of the early structure are present within the mine but have no bearing whatsoever on the distribution of ore. The folding discussed below belongs to the "Christmas-tree" pattern of folds. Early structure folds are too small to illustrate on small scale maps or cross-sections.

Structure.—The detailed fold structure at the Elizabeth mine is outlined by the two amphibolite beds. Apart from these marker horizons and some of the rocks within the main ore zone itself, there are no other rocks sufficiently distinctive to be traced more than twenty or thirty feet along the strike or dip of the beds.

Of the two amphibolites, the apparently higher stratigraphic member [5] is called the Westwall amphibolite, and the lower one the Footwall-Hanging-

[5] As discussed previously, the rocks forming the Orange structural syncline, of which the two above mentioned amphibolites are part, are overturned so that in cross section the stratigraphic sequence is reversed. To avoid confusion, it is proposed from this point on to refer to anticlines, synclines, upper beds, or overlying beds by their present structural positions, and not by their true stratigraphic definition, e.g., Elizabeth syncline, not Elizabeth anticline (stratigraphic).

wall amphibolite.[6] These two are marked as beds G and H on the surface map (Fig. 3), and their structure illustrated in Figures 5 to 8. Folds shown on these cross-sections plunge north, horizontal, and south. The Elizabeth syncline (S1) plunges 10 to 14 degrees north in the southern section of the mine, is approximately horizontal in the central section of the mine (13000N to 15500N) and reverses to 7 degrees south in the northern section before

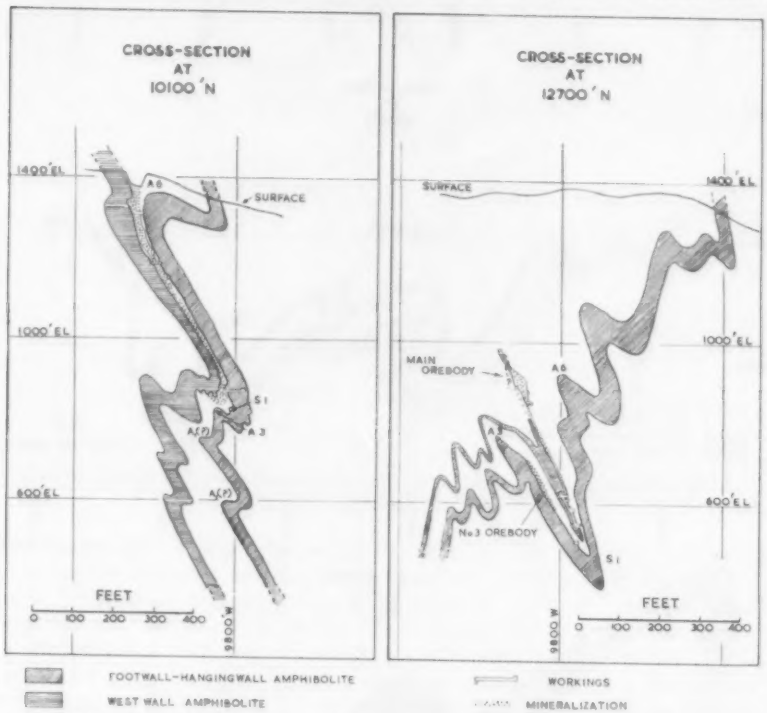

FIG. 5. (Left) Cross-section at Coord. 10100N looking north.
FIG. 6. (Right) Cross-section at Coord. 12700N looking north.

losing its identity between 17200N and 17700N. The doubly plunging anticline (A1) plunges at approximately 10 degrees north from 20000N to 22500N and approximately 9 degrees south from 20000N to 15100N. Farther south from 15100N, this anticline is beneath the surface, and its position is uncertain. However, in light of the way anticline A3 converges on S1 between 15100N and 10100N, it is thought likely that A1 may be represented by one of the anticlines marked A1? at 10100N (Fig. 5).

[6] This terminology arose because, prior to the work of McKinstry and Mikkola, it was believed that the two amphibolite limbs on either side of the main ore zone were different beds, and, as a result, were given different names; the bed on the west side was called Footwall amphibolite, and that on the east side Hangingwall amphibolite.

The diversity in plunge of the various folds shown in Figures 5 to 8 from flat north to flat south is accompanied by a much greater degree of variation in smaller folds. It is common to find in distances as little as thirty feet that plunge observations vary from as much as 30 to 40 degrees south to 30 to 40 degrees north, with a great number of smaller angles of plunge between

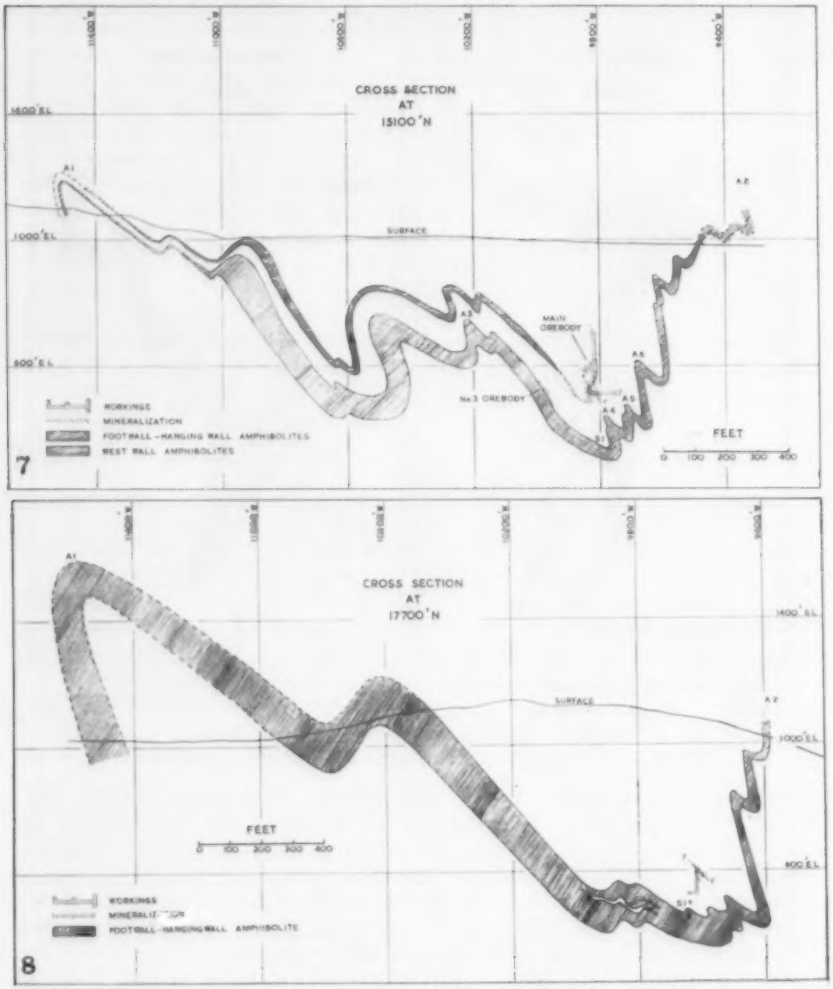

FIG. 7. (Top) Cross-section at Coord. 15100N looking north.
FIG. 8. Cross-section at Coord. 17700N looking north.

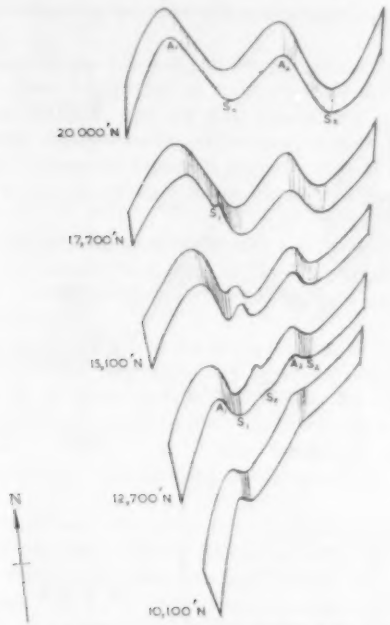

FIG. 9. Block diagram showing the interpretation of folding in the Footwall-Hangingwall amphibolite at the mine.

these extremes. Plunge observations as little as five feet apart are noted to be highly divergent and commonly oppositely plunging. In the backs of some development headings, *en echelon* patterns of doubly plunging small synclines are observed in which the offset pattern is always right-handed.

Minor folded folds and cross-folds are also observed. Cross-folds, in the sense used here, are folds that are creased or buckled in such a manner that the axis of the folds and of the buckle make distinct angles with one another. Both in this instance, and in the case of the folded folds (Fig. 11c), axial plane cleavage is distorted, and indicates that such features are formed late in the development of the overall fold structure.

Figure 9 is a simplified block diagram showing the gross relationships between anticline A1 and syncline S1 as outlined by the Footwall-Hangingwall amphibolite. Other folds shown in Figures 5 to 8 have been deleted to clarify the overall features. Synclines S4 and S5 are represented as one syncline, Sx, which at 20000N may also incorporate S6.

The fold configuration of A2 and S2 is interpreted from surface data alone, and as can be seen from Figure 3, both folds are eroded south of 17700N. However, a surface study of the trend of the axial trace of the Orange structural syncline (S2), its shape in successively lower beds and observed south-

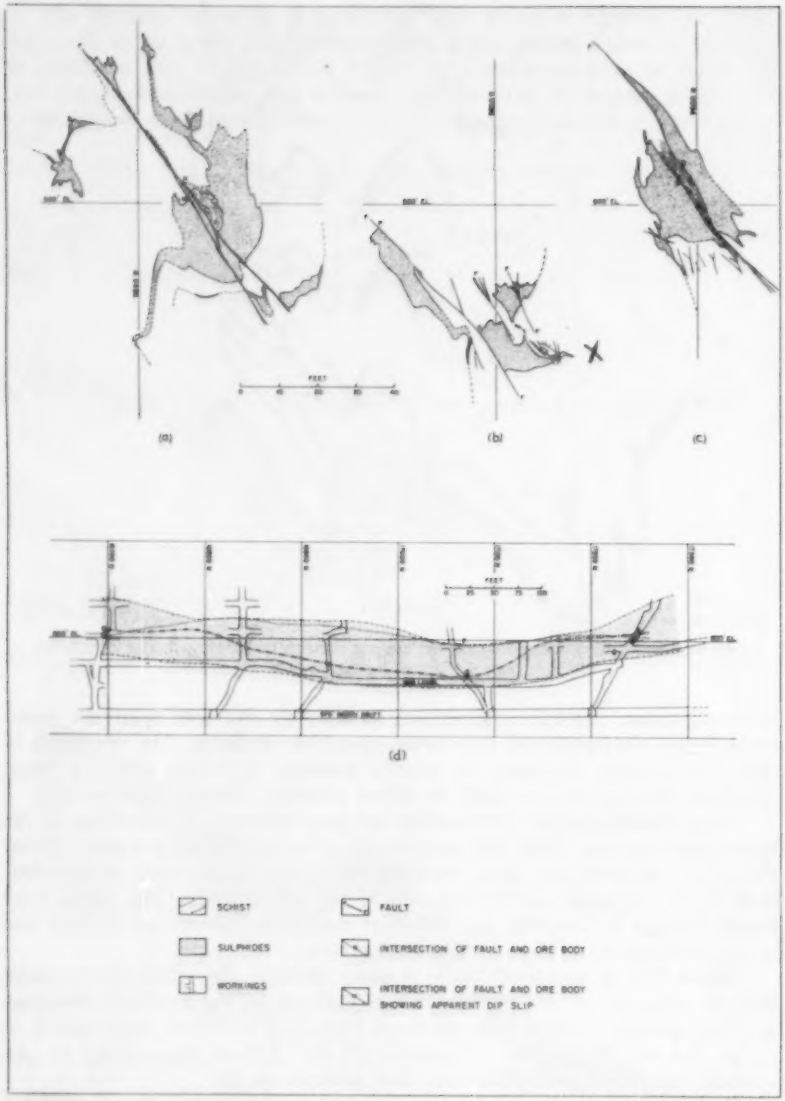

FIG. 10. (a), (b), and (c) are cross-sections of the main ore zone at 16700N, 17090N and 17250N respectively. All cross-sections face north. (d) Longitudinal section of the main orezone between 16700N and 17300N.

erly plunge convince the writer that the interpretation shown in Figure 9 is basically correct.

The doubly plunging *en echelon* pattern of folds exhibited by folds A1, A3, S1, and Sx is thus interpreted to exist in folds A2 and S2. No drill holes exist north of 20000N, and for this reason, the sub-surface fold configuration is unknown farther north. However, even without such information, the fold pattern shown in Figure 9 suggests that the *en echelon* pattern is right-handed in offset as are *en echelon* minor fold patterns in the underground workings.

Faults.—Both pre-ore and post-ore faults are present in the mine workings. Although identification of a fault as pre- or post-ore is generally possible, it is difficult to determine to what extent post-ore faults occupy the sites of the pre-ore faults.

Pre-ore faults can be identified by the presence of sulfides in the fault. The sulfides in general are segregated as lenses, which may range from a few inches to twenty or thirty feet in length, and lie either in the fault or against the hangingwall side of the fault. Such ore is shown midway along the fault illustrated in Figure 10a. These lenses of ore may finger into schists along the schistosity and bedding as illustrated at the top of the fault in Figure 10a.

At the south end of the mine, some relic faults are recognized. They are both bedded and oblique faults which are infilled with extremely fine sulfides. It appears that the fineness of grain size results from the replacement of fault gouge by the sulfides. In many exposures, it is apparent that pre-ore faults are "tight" and are not accompanied by brecciation or gouge, and have little, if any, displacement.

Pre-ore faults are strike faults parallel to the axial planes of the minor folds. In the southern section of the mine where the orebody is more tabular in shape (Fig. 15) than in the north, faults are deflected by bedding, and for this reason are commonly observed to be bedding shears.

In the No. 3 ore zone, ore infills the core of *décollement*-like folds in which the relatively incompetent schists have slid on a base of amphibolite (Fig. 14c). Such folding is accompanied by bedding plane shears at the base of the fold.

Post-ore faults are much more conspicuous and are characterized by the presence of abundant gouge. They have a maximum width of three feet and have, in places, large open cavities. Post-ore faults are most prominently displayed in the north end of the mine where they, in part, occupy the sites of pre-ore faults. The reactivation of the pre-ore faults causes brecciation and gouging of the sulfides present in the pre-ore faults. Separate post-ore faults develop concurrently with the reactivation of the older faults and commonly occur in groups forming a zone of faulting in which faults form an *en echelon* pattern with one another. Individual faults die out along bedding planes or splay out into horsetail patterns (Fig. 10b). Fault movement is variable, and the direction of displacement on one fault is not necessarily the same as that on an adjacent fault.

Since the faults are strike faults, the determination of net slip is very

difficult. However, the conclusions of the study are that the faults are predominantly gravity faults. Isolated strike slip faults have been noted although generally the strike slip component on faults is small or negligible.

In the main ore zone, normal displacement predominates. Some reverse faults occur but are much less common. The latter have a maximum observed displacement of four feet compared to the maximum observed displacement of forty feet on a normal fault. In only one instance has the strike slip component of a main ore zone strike fault been positively determined, but this was possible where an east-west striking vertical post-ore dike transects the ore zone. The dike was later cut by faults. The displacement is eight feet, west block north. Based on less accurate methods of determination, it is believed that the maximum order of strike slip movement is eight feet.

Figure 10 is an illustration of the fault zone at the north end of the mine workings. (a), (b), and (c) are three cross-sections spaced over a strike distance of 600 feet. The letters MN, PQ, and RS show the dip slip component on faults at each locality. Figure 10d is a longitudinal section showing the positions of MN, PQ, and RS together with a multitude of other observations along the fault. The fault on the whole is normal, but at either end of the area becomes reverse. To the south, the fault rapidly changes to a normal fault, while, to the north, there is no additional information. Determination of strike slip component shows that the maximum movement varies from zero to two feet, and the suggestion is that the fault is mainly a gravity fault.

The doubly-hinged nature of the fault is unusual and perhaps indicates the complex stress conditions that were only in part relieved by the pre-ore faulting. Certainly complex stress conditions were present during the original folding as neither sections (10a) nor (10c) show any abnormalities in their structural shapes, but extreme deformation of folding and cleavage developed between the two points. In section (10b) point X is the axis of a recumbent deformed syncline. The fold becomes progressively less recumbent to the north and south and develops into a syncline with an undeformed axial plane dipping approximately 58° east.

It appears that the later deformation, to which the post-ore faults belong, was at least in part relieved by movement along pre-existing faults and zones of weaknesses. Figure 11c illustrates the movement of a fault in the same general area as Figure 10b. Evidence suggests that the fault is wholly post-ore. The sequence of development leading to the relations revealed in Figure 11c are shown in Figures 11a and 11b. Folding and axial plane slip cleavage were developed before incipient opening of the bedding laminae and introduction of the ore solutions. The rotation of anticline A either proceeded during the opening of the beds and introduction of ore or alternatively after the sulfides were introduced. The fault transects the rotated fold and is accompanied by brecciation and offset of the ore as well as part of the anticline.

Age of Faults.—Evidence already presented shows that pre-ore faults developed during the deformation that gave rise to the regional "Christmas-tree" structure, and are accepted as being part of the Acadian orogeny (middle and/or late Devonian).

The post-ore faults are post-folding and metamorphism and can be dated as being younger than the Mississippian (?) metadiabase dikes, which they truncate.

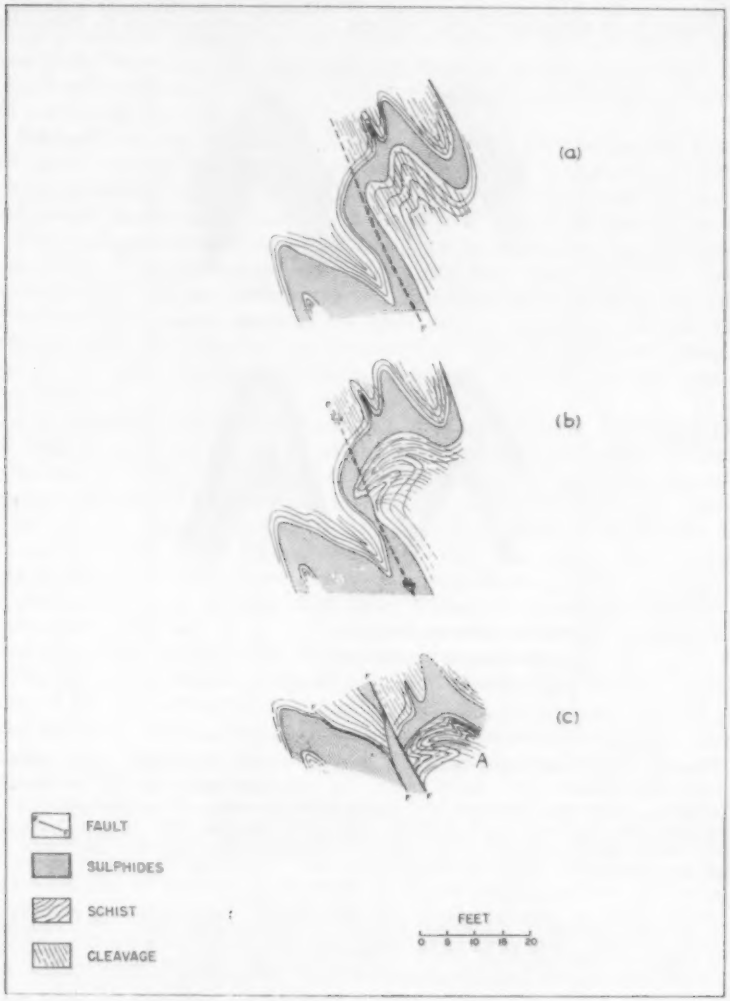

FIG. 11. (c) Cross-section in the main zone at 16770N. (Facing north.) Elevation approximately 600 feet. Fault is post-ore. (a) and (b) Reconstructed cross-sections showing the hypothesized sequence of events leading to (c). Dashed line represents inferred position along which faulting occurred.

FOLIATION

Four types of foliate structures are present in the area and are (1) the almost universal bedding schistosity (Fig. 12a), (2) axial plane slip cleavage (Fig. 12b), (3) gradation of bedding schistosity into a schistosity that passes gradually from parallelism with bedding on the limbs of folds to parallelism

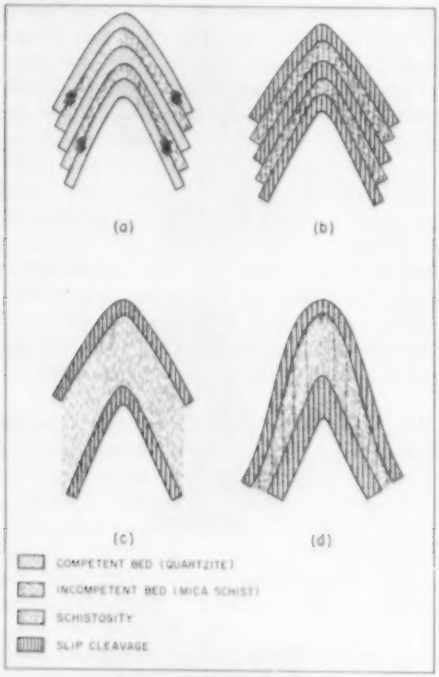

FIG. 12. (a) Bedding schistosity in mica schist interbedded with quartzite or quartzitic schist. (b) Axial plane slip cleavage superimposed on bedding schistosity. Cleavage intersects and displaces schistosity. (c) Axial plane schistosity and slip cleavage. (d) Bedding schistosity grading into axial plane schistosity in the apical position of a fold. Axial plane slip cleavage intersects and displaces schistosity.

with the axial plane in the apical position of folds (Fig. 12d), and (4) possible local examples of axial plane schistosity (Fig. 12c). As this schistosity has been seen only in apical positions of large folds, the possibility exists that it is actually (3). The writer cannot confirm the presence of axial plane schistosity. Presumably it would be present where isoclinal folds existed.

Slip cleavage is developed later than bedding schistosity and the modified bedding-axial plane schistosity (3) and transects them.

Schistosity.—The term schistosity is used to designate the parallel orientation of platy minerals including muscovite, biotite, and chlorite, and the elongation of the non-micaceous minerals. The mineral orientation is predominantly parallel to bedding, and the writer believes that this fact is related to the origin of bedding lineation of hornblende in the amphibolite beds of the district. Textural relations suggest that the growth of metamorphic minerals largely preceded deformation. The preferred orientation of hornblende crystals lying in the bedding planes of fine-grained and non-gneissic amphibolites indicates that hornblende grew by mimetic crystallization.

Inferred from the above facts, it seems likely that foliation parallel to the attitude of bedding has a similar origin, that is, that the growth of micas parallel to bedding occurred during the process of mimetic crystallization. It is suggested that had deformation and the thermal peak of metamorphism coincided, axial plane schistosity would have been the dominant foliate structure of the area. The presence of modified bedding-axial plane schistosity illustrated in Figure 12d can be interpreted as a modification of bedding schistosity in the thickened apical positions of folds during subsequent deformation. Although I have not observed modified bedding-axial plane schistosity superimposed on relic bedding schistosity, Rosenfeld (p. 93) reports such a phenomenon.

Slip Cleavage.—Slip cleavage, in the sense used here, is a cleavage that has much in common with both axial plane cleavage and fracture cleavage as defined by Billings (p. 339). It is characterized by individual planes of cleavage that can be measured, and which vary in spacing from as much as 60 and 70 mm down to the fineness of schistosity. Most commonly the distance is 0.5 to 3.0 mm. Where the cleavage cuts the schists, small crenulations or drag folds are apparent in the micaceous minerals. The slip cleavage occupies a position of an axial plane shear or zone of attenuation along which displacement, that may be as much as half an inch, commonly occurs. Observations of the cleavage show that, where it is more strongly developed, the spacing between individual planes becomes less, and the angle between opposite limbs of the crenulation becomes smaller until the crenulations have an isoclinal structure. Mica plates immediately against the slip cleavage plane attain an orientation that is parallel to the slip cleavage and to the axial planes of the overall folding (Fig. 4).

The difference between fracture cleavage and the slip cleavage here is borne out by the fact that slip cleavage develops parallel to the lengthening of the rocks as a whole and to the axial planes of folds, and not at an angle between 0 and 45 degrees, as required by the mechanics of fracture cleavage. Moreover, detailed study shows that the displacements on some adjacent parallel slip planes are in opposite directions. Although this cleavage is characterized by parallel shears, it does not agree with the mechanics of shear cleavage described in texts.

Field data previously described indicate that cleavage is intimately related to the formation of the Strafford dome. The cleavage forms an arch that wraps about the dome in general conformity with the overall shape of the dome as outlined by the Standing Pond amphibolite.

Lineation.—Lineation is conspicuous within the mine workings, and is apparent as axes of major and minor folds, intersections of cleavage with bedding, crinkles or small drag folds formed at the intersection of cleavage and bedding schistosity, elongation, and streaking of biotite, boudinage, and slickensides. Of these, the most prominent is the crinkling seen in the schists. Mine drifts strike north and for this reason the east and west walls are bounded by steeply-dipping bedding planes on which schistosity crinkles are present. The plunges change constantly in gentle longitudinal curves over a range of forty or more degrees. The mean of such plunges in a given fifty foot length of drift approximates the known overall plunge of major fold axes.

Biotite flakes lie in the plane of bedding schistosity and are elongated and streaked down the limbs of folds at right angles to the axes of the folds. Such biotite streaks are several inches long in places and are seen in great numbers on the walls of drifts. They are mostly at right angles to crinkles although they vary by as much as twenty degrees either side of normal.

The only amphibolite that shows marked mineral lineation is the fine grained needle amphibolite. Lineation of hornblende is either weakly developed or not developed at all in medium and coarse-grained amphibolites.

In the needle amphibolite bed of the Standing Pond member, the hornblende laths lie in the bedding planes, and no instance of *b* lineations was seen. However, the present discussion is based largely on observation in the mine, and a full examination of the Standing Pond amphibolite was not made. All lineation noted, nevertheless, shows orientation parallel to the bedding planes, and in those instances where fold axes or plunge observations are present, lineation shows a tendency to be at right angles to such features, but in general is randomly oriented within the plane of the bedding. Where lineation is parallel to the plane of the bedding, it is evidently due to mimetic crystallization.

OREBODIES

The Elizabeth mine orebodies are known as the main orebody, and the No. 3 orebody. Both of them, as far as can be ascertained, maintain their respective stratigraphic horizons through their known length. Figures 6 and 7 illustrate the relative positions of the two orebodies to one another at the south and north ends of the mine.

Scattered sulfide zones can be traced along both horizons out of the ore zones, and traces of sulfides can be followed 1,500 feet to the surface in the case of the 15100N cross-section (Fig. 7).

The No. 3 orebody occupies a zone between the Footwall amphibolite and overlying schists on the western limb of the Elizabeth syncline (S1). It has been mined sporadically between coordinates of 14200N and 16700N. To the north of the last mentioned point, mineralization is not evident. Due to thinning of the schists in the mid-section of the mine (12000N), the two amphibolite horizons are close to one another and the No. 3 and the lower part of the main ore zone merge into one another for some distance. To the

south beyond 12700N, the No. 3 orebody dies out as the limb distance between A3 and S1 shortens. Only weak mineralization exists at 10100N (Fig. 5).

In detail the thick ore sections of the No. 3 orebody are associated with folding of two kinds, illustrated in Figures 13 and 14c. The folding illustrated in Figure 13 is uncommon. It appears that the competency of the

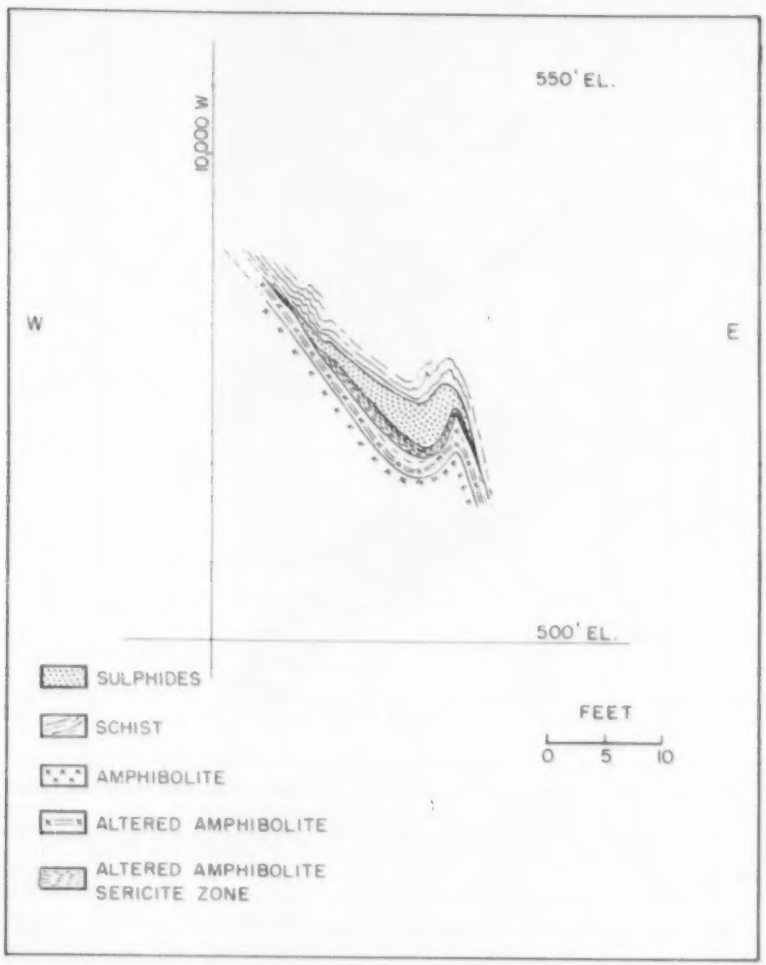

FIG. 13. Relationship of an oreshoot to drag fold structure in the No. 3 orezone at 16890N.

thick amphibolites was so great that, in general, incipient open space developed by the sliding of the schists on the amphibolite without development of any folds in the amphibolite itself.

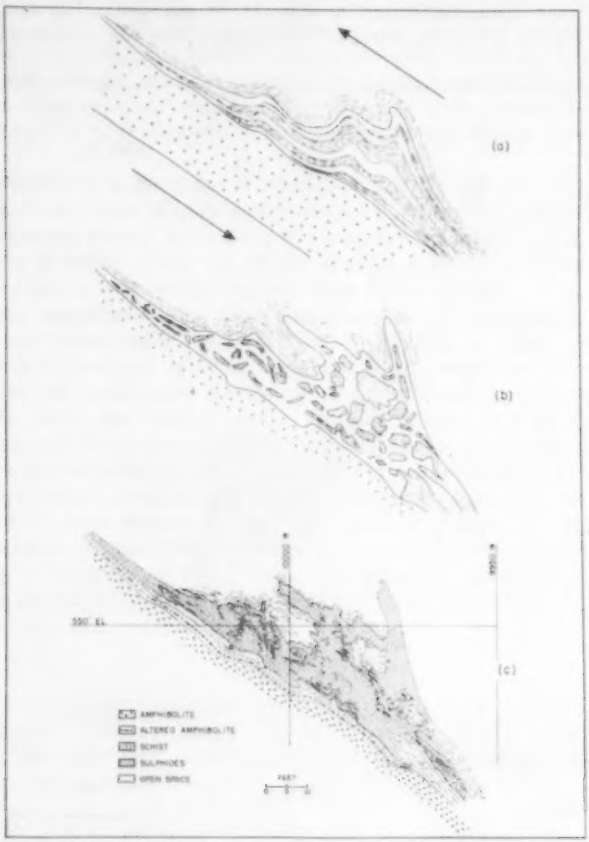

FIG. 14. (c) Cross-section of the No. 3 ore zone at 15970N, illustrating schist breccia and relationship of the oreshoot to fold development in schist. (a) and (b) Reconstructed cross-sections showing the hypothesized sequence of events leading to (c). (a), (b), and the introduction of sulfides are thought to be contemporaneous.

The main orebody is a continuous oreshoot 11400 feet in known length. Mining and open pit operations have been carried out over approximately 10,000 feet of this length. The shoot occupies a zone between the Westwall amphibolite and schists on the eastern limb of the Elizabeth syncline (S1).

The lower limit of the orebody is the keel of the syncline, and the upper limit, through the central and southern sections of the mine, coincide with the lensing out of the amphibolite. At the south end of the mine, the main ore zone is a tabular-shaped body 600 feet in vertical height (Fig. 15), but its shape is progressively modified to the north where it loses its tabular shape

FIG. 15. Relationship of main ore zone orebodies to drag folds in the Westwall Amphibolite in the southern section of the mine (approximately 10000N).

(Fig. 10). This modification is coincident with the narrowing and lensing out of the Westwall amphibolite horizon adjacent to the ore zone, as well as the dying out of the Elizabeth syncline (S1).

The overall plunge of the main ore zone is 10 to 14 degrees north in the southern two-thirds of the mine and approximately zero in the northern section, although in the northernmost thousand feet of the mine workings, the plunge reverses to seven degrees south. The strike of the ore zone is approximately N5°E, and the dip variable from 60°E to 90°.

At the northernmost end of the mine, the vertical height of the main ore zone is fifty feet, and the shape is that of an overturned west-block-up drag

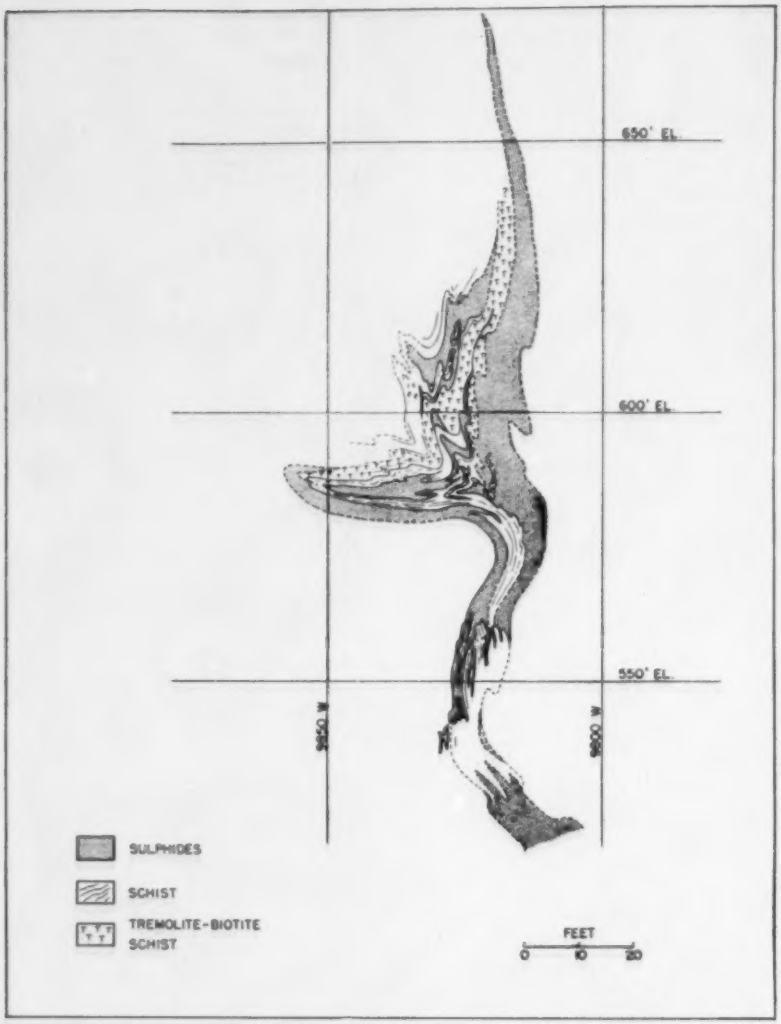

FIG. 16. Cross-section of the main ore zone at 15000N. Sulfides are concentrated in apical positions of folds but are absent from the attenuated limbs of the same folds.

fold, as illustrated in Figure 10. Three mineralized zones are present at 16700N (Fig.10a), and at 17700N the ore zone consists of six or eight superimposed synclinal saddle reef-like lenses of sulfides four to five feet apart and is of uneconomic grade.

The greatest thickness of ore is associated with drag fold positions (Figs. 15, 16) and attains a maximum thickness of sixty feet in the apical position of the fold. Figure 15 shows that beneath drag fold positions, the ore zone becomes progressively narrower down the limb towards the lower drag fold,

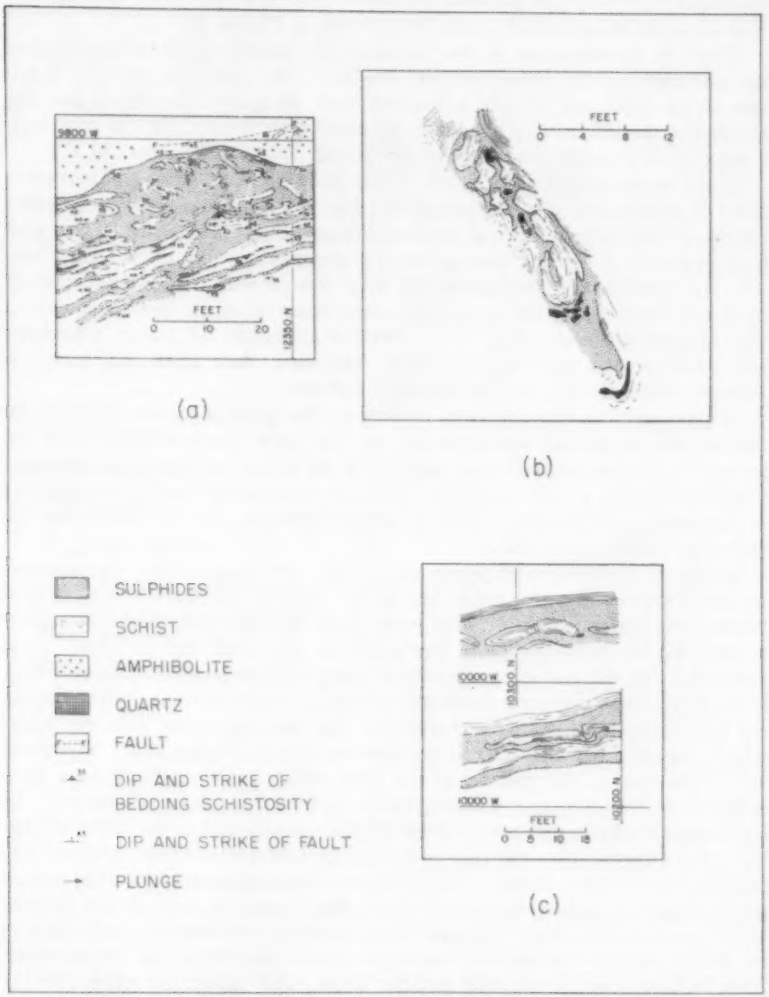

FIG. 17. (a) Sketch of schist breccia. Plan of the back in 975-250 stope. Elevation 665 feet. (b) Schist breccia in a matrix of sulfides. 480 stope raise at 14970N. (c) Different stage of boudinage in the same schist band 300 South Drift. (All three figures after McKinstry and Mikkola, 1954.)

and reaches a minimum thickness of approximately five feet before it increases rapidly to 40 to 60 feet in the area below the lower drag fold. In the narrow areas, the ore zone may lack sulfide lenses altogether and be represented by a zone of scattered sulfides of uneconomic grade. A detailed illustration depicting the presence of ore in drag fold positions and the absence of ore in straight limb positions is shown in Figure 16.

Mode of Emplacement of the Sulfides.—As stated, the dominant feature that distinguishes the shapes of both the main ore zone and the No. 3 ore zone is the thickness of ore associated with drag fold positions, and the thinness of the ore in straight limbs between drag folds. This is true both in the overall structure and in structures down to one foot or less in size.

In the larger drag fold positions the orebody consists either of alternating lenses of sulfides and interbanded schist (Fig. 16) or of massive sulfide bodies containing both large and small randomly-oriented blocks of schist, which give the appearance of a schist breccia set in a groundmass of sulfides (Figs. 14c, 17). In general, the brecciation has been too extreme and replacement of schist fragments too great to attempt reconstruction of the breccia blocks to their original positions (Fig. 17). Pre-ore faults are, in places, associated with schist breccia and, as previously mentioned, their associated gouge is commonly replaced by very fine-grained sulfides.

If one were to imagine open spaces in the positions now occupied by sulfides, the suggestion would clearly be that open space resulted from the flexing and opening of individual laminae of the schists similar to the openings formed by flexing a deck of cards. Such positions are generally accompanied by brecciation and faulting, both of which diminish and die out down the attenuated limbs of the folds.

However, differences in grain size of the ore suggest that the ore was not emplacement in open space, but rather that, as the structure started to develop, the formation of incipient open space and brecciation caused a great increase in the permeability of the rocks in the drag fold position. It is postulated that the ore solutions passed along such permeable zones and that, as the incipient open space developed, wholesale replacement of schist breccia and precipitation of sulfides proceeded. In time not only was the schist breccia replaced but also part of the wall rock as in Figure 18b. The grain size of the bulk of the sulfides in the mine which are thought to have been emplaced in this way is medium grained (0.1 to 0.5 mm in diameter). In some small fractures that are offshoots of the orebody and crosscut the stratigraphy for several feet, the ore is commonly extremely coarse grained and suggests open space filling. Proof of the contemporaneity of the coarse-grained ore with the medium-grained ore that forms the bulk of the orebody is that identical bleaching and wall rock alteration accompanies both types of ore (Fig. 18b). The sulfides were introduced under garnet metamorphic grade, which would imply that sulfides were stable under the particular PT conditions prevailing at that time and would not suffer any recrystallization then or during the decreasing PT conditions which followed.

There appears to be a relationship between the extent of the main ore

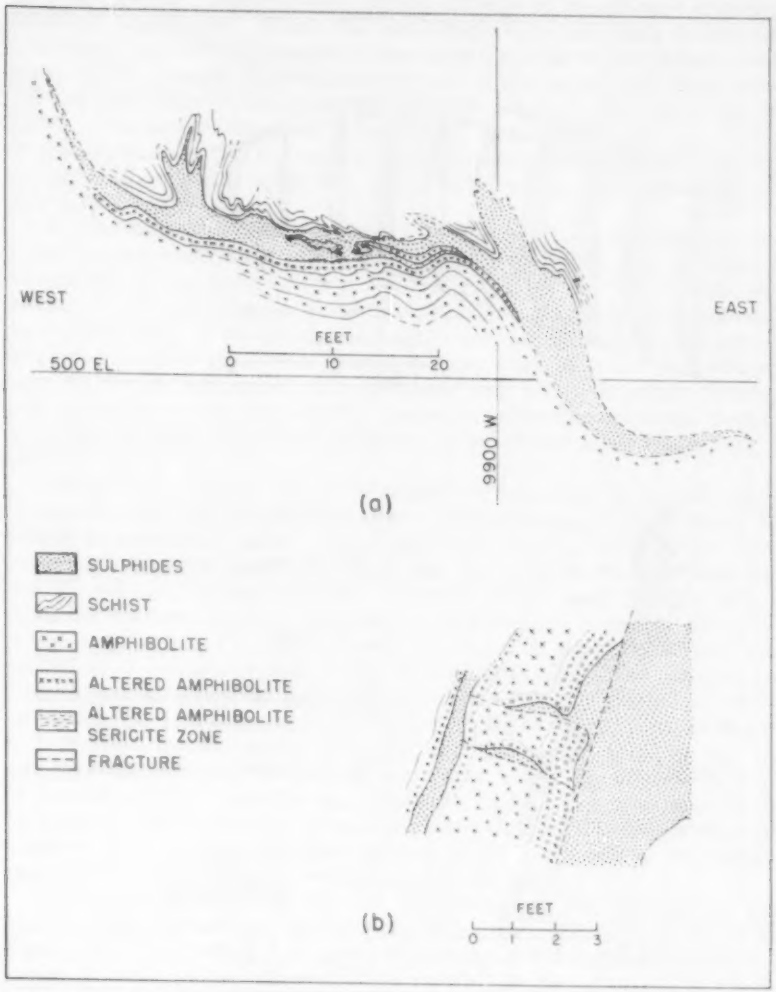

FIG. 18. (a) Cross-section of the No. 3 oreshoot at 14190N illustrating the relationship of an oreshoot to drag fold structure. (b) Fracture in amphibolite filled by sulfide. Amphibolite partly replaced by sulfides? Sulfides are coarse-grained in fractures but medium-grained in ore zone. Cross-section facing south. 300-200 raise at 10145N, 10000W, elevation 1,305 feet. (After McKinstry and Mikkola, 1954, page 19).

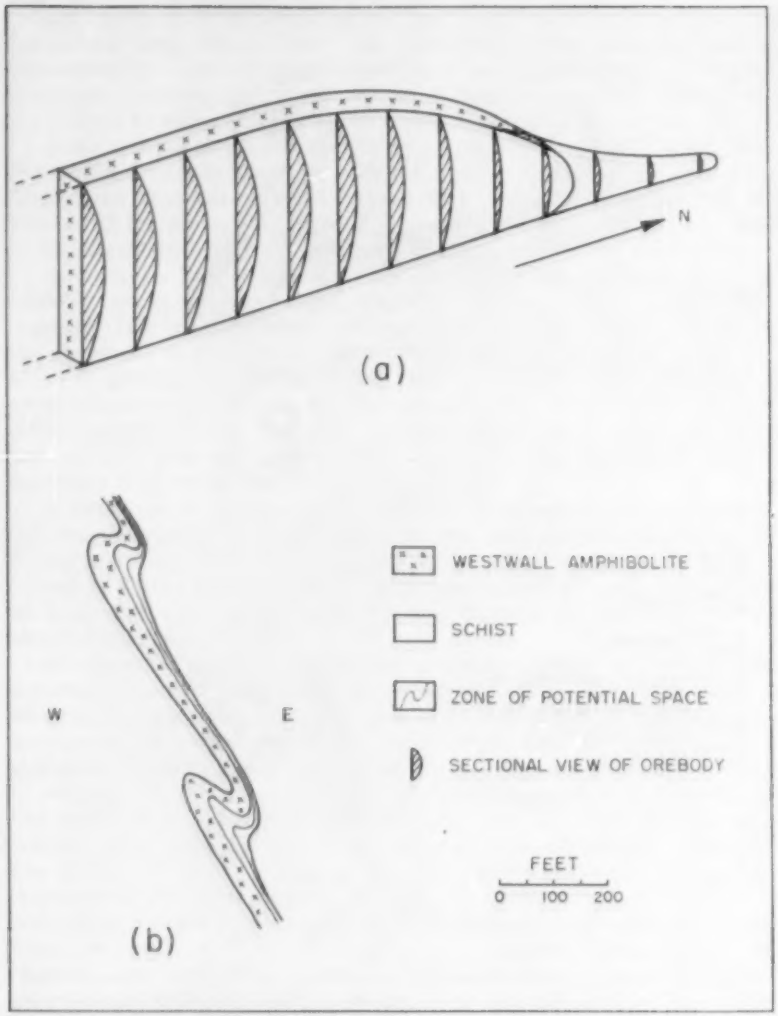

FIG. 19. (a) Diagrammatic sketch illustrating the relationship between the extent of the main ore zone and the extent of the Westwall amphibolite. (b) Diagrammatic cross-section of the main ore zone showing the development of potential open space associated with dragfold structure. Ore, interbedded schist and schist breccia now occupy such sites.

zone vertically and longitudinally and the presence of the adjacent lenticular Westwall amphibolite. Where this amphibolite thins and starts to lens out northward from 12700N, a rapid diminution in the height of the orebody takes place. Only sporadic discontinuous sections of the amphibolite lie between 12800N and 16000N, and these are generally not more than three feet in width. The amphibolite is not evident at all past 16000N, and it is in this section of the mine that the vertical height of the orebody rapidly diminishes to fifty feet and finally splits into six or eight bedded sulfide stringers and dies out.

It is felt that the relative competency of the amphibolite together with the variable competency of the adjacent schists is the major ore control. This is exemplified by the No. 3 ore zone area. Figures 14c and 18a illustrate the folding of schists by slippage along the contact of a thick competent unfolded amphibolite bed. If the schists had been of uniform competency, it is postulated that complete adjustment by rock flowage would have occurred. However, the varying competency of the individual beds within the schist, (quartzites, quartzitic schists, and schists) prevented adjustment by rock flowage alone and developed incipient open space and brecciation along which the ore solutions moved.

The fact that ore does not extend beyond its determined limits and occurs in random drag fold positions adjacent to amphibolite elsewhere cannot be related to competency of the amphibolite alone. In the study of the mine ore zone, it becomes readily apparent that the rocks interlayered with the ore are different lithologically from the rocks of the same horizon farther down the dip away from the ore zone, and different too from the rocks generally found adjacent to other amphibolite beds. In short, these rocks are distinctive in appearance and consist of biotite-tremolite schist, plagioclase-tremolite gneiss, a thin discontinuous amphibolite bed, and interbedded schist and quartzite. It is believed that during the folding of the schists in the Elizabeth syncline, the alternating competent and incompetent rocks of the ore zone were able to adjust to the shape of the drag folds in the amphibolite only by a combination of rock flowage, brecciation, and development of incipient open space. Such permeable zones, favorable to localization of hydrothermal solutions, did not form elsewhere because of the uniformity of the incompetent schists adjacent to the massive amphibolite bands.

The hypothesized reason for the continuance of the ore zone to the north beyond the northern limits of the Westwall amphibolite is shown in Figure 19a. The folding that caused the parting of bedding planes and brecciation of rocks against the amphibolite resulted in the formation, in effect, of a potential opening of an elongated sheaf that projected somewhat past the limits of the amphibolite before being dissipated in the schists to the north.

The above hypothesis suggests that the loci of orebodies in the district as a whole are against flexed or folded thick competent amphibolite beds in contact with schists interbedded with quartzites, quartzitic schists or other rocks relatively more competent than the schists themselves. The possibility of

finding ore associated with quartzite beds is slight because such beds invariably are quite thin, seldom more than two or three feet in thickness. Such thin quartzite bands within thick beds of schist do not have the rigidity or competence of thick beds of quartzite and, in fact, fold with flexibility comparable to that of the schists. Amphibolites, on the other hands, are massive and reach thicknesses as great as 200 feet.

In support of this hypothesis, it is pointed out that, almost without exception, mines, prospects, and pits of the Orange County copper district are on the contact of amphibolite beds. Chemical favorability of the amphibolite beds would appear to be ruled out as orebodies are seldom found in the amphibolite itself. Generally, the only sulfides in amphibolite are those that have diffused in from orebodies on the contact of amphibolite or have been precipitated in fractures and permeable zones along which movement of hydrothermal solutions could take place.

ACKNOWLEDGMENTS

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Appalachian Sulphides Incorporated, and their officers made this study possible by their help and cooperation. The general manager, Mr. J. F. Cowley, and the assistant manager, Mr. C. B. Benson, employed the writer for a period of twenty months to pursue this study.

BROKEN HILL,
NEW SOUTH WALES,
AUSTRALIA,
June 25, 1958

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AMYGDULE MINERAL ZONING IN THE PORTAGE LAKE LAVA SERIES, MICHIGAN COPPER DISTRICT[1]

RICHARD E. STOIBER AND EDWARD S. DAVIDSON

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PART I

ABSTRACT

In the Portage Lake lava series of the Keweenaw Peninsula, Michigan, three overlapping amygdule mineral zones—prehnite, epidote, and quartz zones, respectively—can be distinguished. Higher stratigraphic horizons typically lie within the prehnite zone and lower horizons within the epidote and quartz zones. Zone boundaries cross stratigraphic horizons, indicating that the amygdule minerals were deposited after many successive flows were extruded. Temperature control of the overall distribution is likely. Mineralogy of flow tops of the Keweenawan series throughout the Lake Superior basin is like that of Keweenaw Peninsula, indicating that the mineral zones have regional extent.

Copper concentrations are commonly near the boundary of the quartz zone, but may lie well within the quartz zone where quartz is not abundant. Most barren areas and unsuccessful mines lie either well outside the quartz zone, or where quartz or prehnite or both are plentiful. Detailed mineral mapping of mines on the Kearsarge amygdaloid shows that quartz is a prominent mineral only in the deeper portions of the mined area and that major concentrations of copper lie near the boundary of the quartz zone.

In the Kearsarge amygdaloid deposition temperatures of quartz and calcite, determined by inclusion thermometry, reach a maximum of about

[1] A large part of the material in this paper was presented on February 19, 1955, before the Society of Economic Geologists, at the joint meeting of the Society of Economic Geologists and the American Institute of Mining and Metallurgical Engineers in Chicago, Ill. Publication authorized by the Director, United States Geological Survey.

360° C; this indicates a temperature gradient of greater than 2° C per 100 feet at the time of deposition, in contrast to a gradient of 0.6° C per 100 feet at the present time—indicating that fluids of hydrothermal character, rising along the flow top, deposited the amygdule minerals, one of which is native copper. The chemical constituents of epidote, prehnite, and quartz, and the wide distribution and post-extrusion age of these minerals is compatible with formation by regional hydrothermal rearrangement and alteration of material of the lavas as shown by chemical analyses of the altered rocks of the Kearsarge flow top. Pumpellyitization of parts of the flow top, caused by calcium oxide- and carbon dioxide-bearing waters, provided material to alter other parts of the top to albite basalt. Both alteration processes freed chemicals that formed amygdule minerals.

A slightly greater volume of pumpellyitized rock than albitized rock is needed to provide the chemicals required for region-wide formation of amygdule minerals. The suggestion is made that pumpellyitization at depth is more extensive than in the ground now opened by mining and that the chemicals freed were transported regionally upward by hydrothermal solutions. Copper distribution seems related to the zonal amygdule mineral pattern resulting from this alteration and may itself have been freed from the lavas at depth during alteration to pumpellyite.

INTRODUCTION

THIS is a study of a suite of minerals occurring principally in the tops of the lava flows of the Portage Lake lava series on the Keweenaw Peninsula, Michigan. The minerals fill the vesicles and interfragmental spaces in the lava tops; to a minor degree they replace the groundmass of the flow tops and occur in the interstices of sediments interbedded with the lava flows. Because these minerals are most prominently displayed in the amygdules, all these occurrences are for brevity here considered and described as "amygdule minerals." The most common minerals of the suite are calcite, chlorite, epidote, quartz, prehnite, native copper, and laumontite.

This paper suggests a correlation between the distribution of copper and that of other amygdule minerals. Chemical changes in the amygdaloidal flow tops during alteration is considered and data are presented relative to the temperature of formation of some of the amygdules. The age and origin of the amygdule minerals and copper is discussed.

Information presented here resulted from about three man-years of field work and collection and assembly of data by the authors during 1949–1954 from outcrops, mine dumps, drill core, underground workings and records of earlier workers. It represents a continuation, modification and amplification of some phases of study of mineral occurrence and distribution that has been carried on by the Calumet and Hecla Special Survey of 1919–1924, the U. S. Geological Survey in 1924–1925, the Calumet and Hecla resident geological staff since then, and the U. S. Geological Survey group in the area from 1943 to 1954, of which we were members for part of the time since 1948.

The area from which detailed mineralogical information was obtained extends from Victoria, Ontonagon County, Michigan, northeast to the end of the Keweenaw Peninsula (Fig. 1). Much is known about the distribution

of amygdule minerals in some parts of this area, and very little is known in others. Drill-core logs of the Copper Range Company and, most important, the extensive and excellent logs of drill core made by Dr. T. M. Broderick and C. D. Hohl of Calumet and Hecla, Inc., have been a major source of basic data. The writers themselves have studied about 50,000 feet of drill

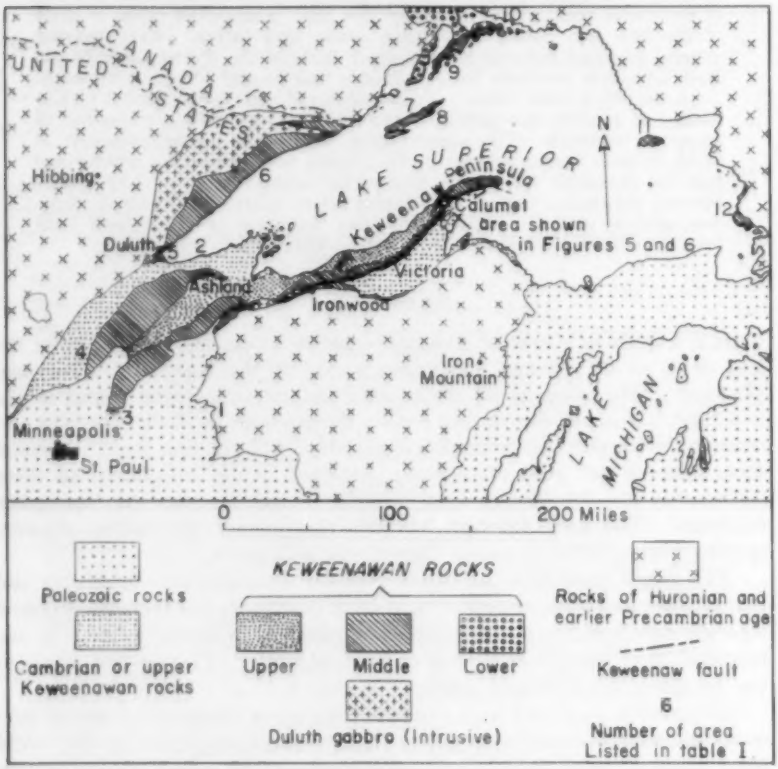


FIG. 1. Index map of the Lake Superior region.

core of the many hundred thousand feet available. They have made mineralogical observations in over 40 miles of underground workings. Rock waste dumps of nearly all the mines and prospects were examined. Some information as to mineral distribution was acquired from outcrops mapped by other members of the U. S. Geological Survey party. Regional information throughout the Lake Superior Basin was largely taken from literature but includes contributions from field work of the authors and also of H. R. Cornwall.

The management of Calumet and Hecla, Inc. and the Copper Range Co. gave permission to make underground observations and study the diamond drill core and core logs at their respective properties. The authors are particularly indebted to Dr. T. M. Broderick, formerly Chief Geologist, and Mr. E. R. Lovell, formerly President, Calumet and Hecla, Inc., for the use of the excellent geologic records to which unlimited access was allowed, and for Dr. Broderick's helpful discussions. The important aid that we have received from Walter S. White, Henry R. Cornwall, James C. Wright, and Carol F. Johnston of the Geological Survey is gratefully acknowledged.

RÉSUMÉ OF GEOLOGY AND MINERALOGY OF THE MICHIGAN COPPER DISTRICT

General Geology

The minerals and copper deposits discussed in this paper are in the flow tops and conglomerates of the Portage Lake lava series of middle Keweenawan age (54). The geology of the district has been very completely described in other publications (13, 36, 10) and is merely summarized here.

The Portage Lake lava series in which the mines occur ranges in minimum thickness from about 8,000 feet in the southwestern part of the district to slightly over 15,000 feet in the northeastern part. The base of the series is not exposed, so it may be much thicker. The series is composed of mafic lava flows (16, 9) and interbedded rhyolitic sediments that constitute about 3 percent of the total section. The entire series is thrust to the southeast over the Jacobsville sandstone (38, p. 680, 692) of late Keweenawan or Cambrian age and is conformably overlain to the northwest by the Cooper Harbor conglomerate (38, p. 680, 690) of late Keweenawan age (Fig. 1). The Jacobsville sandstone is flatlying. Dips in the lava series range from 75 to 25 degrees northwest on the Keweenaw Peninsula, where the rocks form the southeast limb of the Lake Superior syncline.

The individual lava flows are characterized by flow tops 2 to 40 feet thick, most of which are oxidized and reddened, containing abundant disseminated hematite and a variety of amygdule minerals of contrasting color. The lower parts of the flow tops are sparsely amygdular, contain less hematite, and grade downward into unoxidized slightly amygdular lava. An unoxidized amygdaloidal unit, 1 foot thick or less, is generally present at the base of a flow, directly overlying the top of the underlying flow. The amygdular flow tops, or amygdaloids, are classified as cellular amygdaloids if the top is relatively unbroken (Fig. 2) and as fragmental amygdaloids if the top is broken into a jumble of fragments (Fig. 3). Both types of amygdaloid may contain sandy and silty detritus or ash in amygdules and between the fragments; these are referred to here as ashy amygdaloids. Many flows with copper-bearing tops or some other distinctive character have acquired local names, such as the Kearsarge, Isle Royale, and Iroquois flows. The tops or amygdaloids of these flows are called respectively the Kearsarge, Isle Royale, and

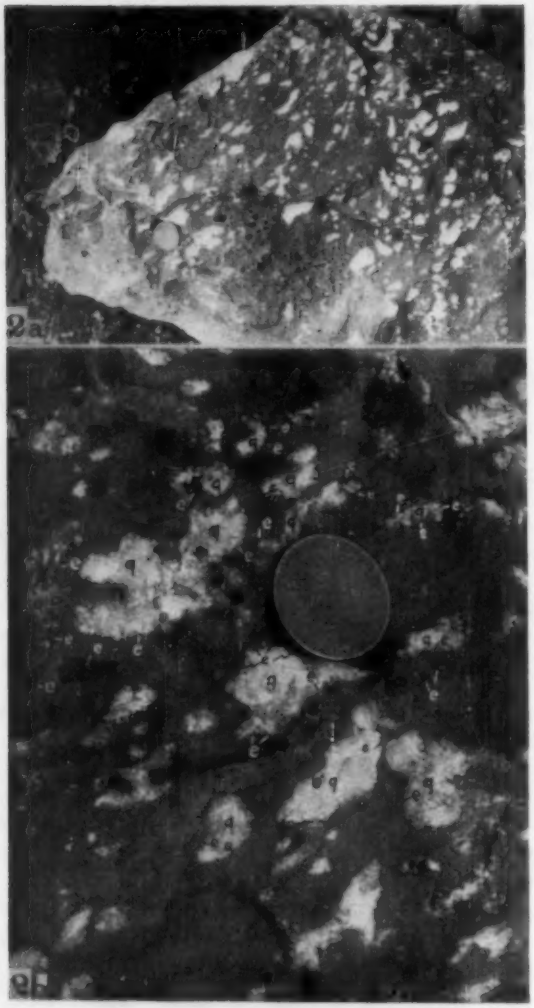


FIG. 2. Typical cellular amygdaloid. Top of Kearsarge flow, North Kearsarge No. 1 shaft, Houghton County, Michigan. A.—Large block. B.—Enlargement of part of A. Epidote (e) lines vesicles; many contain quartz (q) in the center. Representative of lower part of Kearsarge amygdaloid in which red microcline is absent. The groundmass is greenish-gray, due to replacement of feldspar by pumpellyite.

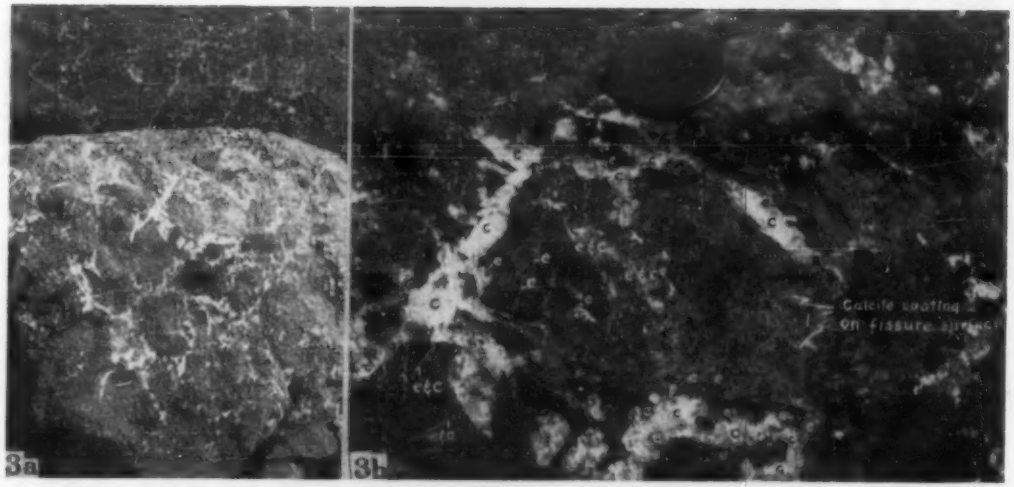


FIG. 3. Typical fragmental amygdaloid. Top of Kearsarge flow, North [illegible] ton County, Michigan. A.—Large block. B.—Enlargement of part of A. The interfragmental minerals and amygdules are calcite (c), epidote (e), and minor quartz (q). Epidote is typically marginal to calcite and fills veinlets in fragments. The groundmass is reddish-brown, due to abundant inclusions of red hematite.

Iroquois amygdaloids. This informal reference to flow tops is followed in this paper.

Copper has been mined from conglomerates, amygdaloidal flow tops, and from fissures or veins that cut across the flows and conglomerates. Butler and Burbank (13) and more recently Broderick, Hohl, and Eidemiller (10) have reviewed the history of the copper mines and their production. The most important mines are shown in relation to the stratigraphy of the Portage Lake lava series in Figure 7. Mines in the Baltic, Isle Royale, Kearsarge,

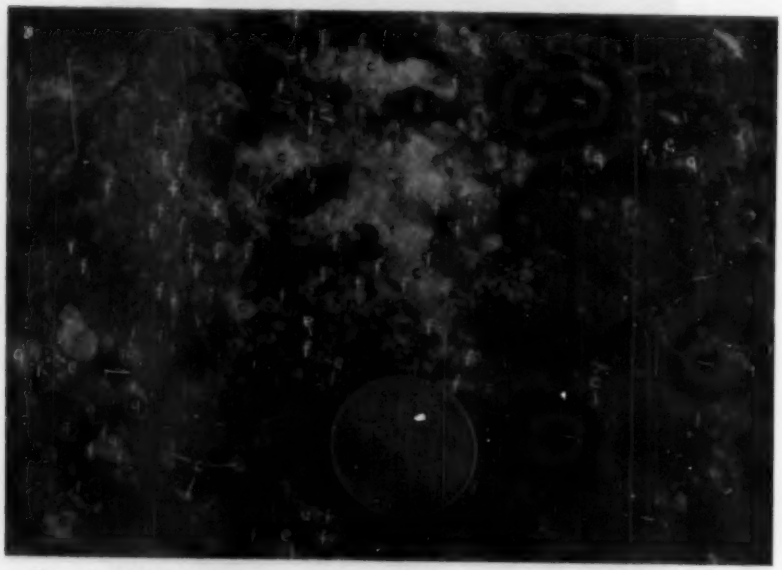


FIG. 4. Fragmental amygdaloid. Top of Kearsarge flow, North Kearsarge No. 1 shaft, Houghton County, Michigan. The veinlets, interfragmental minerals and amygdules are microcline (f), calcite (c), epidote (e), and a very little quartz (q). The marginal site of feldspar and epidote relative to calcite and quartz and the preferred position of calcite in open spaces rather than in narrow veinlets is typical. Representative of the upper part of the Kearsarge amygdaloid.

Osceola, Pewabic and Ashbed amygdaloids have accounted for more than one-half the total district production of approximately 10 billion pounds of copper. The rest has come chiefly from the mines in the Calumet and Hecla (No. 13) conglomerate, which have produced more than 4 billion pounds of copper.

Minerals of the Amygdaloids, Conglomerates, and Fissures

Fifty-one minerals have been described by Butler and Burbank (13, p. 55–62) from the amygdaloids, conglomerates, and fissures. Considerable

information about the geologic occurrences of these minerals is also given by Pumpelly (44), Broderick (7, 8) and by Broderick, Hohl, and Eidemiller (10).

Calcite, chlorite, epidote, pumpellyite, prehnite, microcline, quartz, laumonite, and copper are the only minerals of widespread geographic occurrence that also occur in any one place in notable quantities. All of these minerals in one locality or another replace parts of the flow tops though they are most abundant in the amygdules and in spaces between breccia fragments. Typical associations are shown in Figures 2, 3, and 4.. The same minerals are found in the vesicles of lava pebbles in the conglomerates and calcite, epidote, and microcline occur also in the matrix of the conglomerates. The many other minerals are important only in a few localities or occur in small quantities in widely separated localities and they rarely, if ever, replace any part of the flow top.

The chemical composition of the common minerals is not well known but the optical properties provide some information. Chlorite from the most common occurrence, in the lower part of flow tops, is optically negative, beta in the range 1.602–1.607, with a birefringence of about 0.007. According to Hey (31) this is diabantite; a high silica, low alumina chlorite; the composition is approximately $(Mg_{2.1\text{-}3.2}Fe^{++}_{2.5\text{-}2.1}Al_{0.4})_6\ (Si_{3.6}Al_{0.4})_4O_{10}(OH)_8$.

Epidote from the Kearsarge flow top is optically negative, 2V about 75°, with a birefringence of about 0.040, suggesting, according to Winchell's curves (55, p. 449), that about 27 percent of the aluminum is replaced by ferric iron. The composition is approximately $Ca_2Al_{2.2}Fe_{0.8}^{+++}Si_2O_{12}(OH)$.

Pumpellyite was first described from the Portage Lake lava series by Palache and Vassar (43). More recent information about pumpellyite in general and the optics of the type material has been published by Coombs (15). The approximate composition of pumpellyite is $Ca_4(Al,Fe^{+++})_5(Mg,Fe^{++})Si_6O_{22}(OH)_2\cdot 2H_2O$ (15, p. 122 and 123). From megascopic examination, particularly in underground exposures, pumpellyite appears to occur in amygdules alone, as needles in quartz, and associated with chlorite. Thin-section study indicates that this mineral is more widespread in anygdule fillings that contain epidote than megascopic examination would suggest. The most common occurrence of pumpellyite is as a replacement of masses of the rock of the flow tops (Fig. 2). This hard dense greenish-gray rock makes up large parts of the mined portions of the Isle Royale amygdaloid and is prevalent in the Kearsarge mines.

Prehnite was examined from a number of places in the Iroquois amygdaloid at the Allouez No. 3 mine. It shows a range of beta refractive index of 1.630–1.641. 1.639 was the most common value. This suggests (55, p. 360) that much of the prehnite has the approximate composition $Ca_2(Al_{0.8}Fe_{0.2}^{+++})Si_3O_{10}(OH)_2$.

Microcline has been described from the Michigan Keweenawan by several names: red feldspar (44), orthoclase (13, p. 59–60), and adularia (7). This mineral has been identified as microcline by Klein (32) because of the intercrossed and irregular interpenetration twinning which it exhibits. This

identification has been confirmed by X-ray powder photographs by Fred A. Hildebrand of the U. S. Geological Survey.[2] Microcline collected by Klein, probably from the Ogima amygdaloid in the Michigan E mine, was analyzed by R. B. Ellestad (34, p. 647). It has a very high potash-soda ratio; the potash content is 14.98 percent and soda is 0.17 percent. Microcline in the Michigan Keweenawan is generally colored brick red, a result of countless dustlike inclusions of hematite.

Laumontite is the only zeolite present in large amounts in a great many flows. Laumontite from Michigan has not been analyzed. One may assume that it has the generally accepted composition ($CaAl_2Si_4O_{12}4H_2O$) (14, p. 824). Other zeolites such as analcite, thomsonite, natrolite, chabazite, and heulandite have a much more limited distribution and in most places occur in much smaller quantities.

The wide variety of occurrences of native copper has been discussed by all those describing the geology of the district. Copper occurs in finely disseminated form, in small masses and in very large masses, the largest of which are in fractures. Fine copper is commonly intergrown with prehnite and in some places with calcite and datolite. Small masses most commonly replace the matrix of the flow top rather than fill amygdules or interfragmental open space, and are often associated with rock in which the hematite has been removed, giving rise to the small bleached areas (13, p. 133–135 and 198–199) around copper masses. In other places the associates of copper are quartz, epidote, calcite, and locally megascopic pumpellyite (13, p. 199). Microcline in an amygdule or in breccia filling is not likely to be in contact with copper, but copper is commonly present close by. Copper is rare in the parts of a flow top in which laumontite is prominent.

GEOLOGIC SIGNIFICANCE OF THE AMYGDULE MINERALS

Four types of study have been used to investigate the interrelationships and origin of the minerals of the amygdaloidal flow tops, particularly the relationship of copper to the other minerals. These studies concern (1) the regional distribution of minerals in the amygdaloids of lavas of the Portage Lake lava series of the Keweenaw Peninsula, (2) the mineral occurrences in lavas of Keweenawan age throughout the Lake Superior basin, (3) the distribution of minerals in mines and prospects as gathered from examination of the rock waste dumps, and (4) the distribution of amygdule-minerals within the mines in the Kearsarge amygdaloid both along strike and downdip, and from the base to the top of the Kearsarge amygdaloid. Although each of these four aspects of mineral distribution is considered separately in the following sections, they complement each other, differing for the most part only in the scale at which the mineral relationships are described. The mineralogy of the several large fissures mined for copper has not been studied in detail by the authors, because of the inaccessibility of the workings, but has been described in detail by Broderick (8, 10). The relative ages of certain fissures

[2] Written communication, June 25, 1954.

cutting the Kearsarge amygdaloid and of the amygdular minerals of the flow top are considered in this paper.

Distribution of Amygdule Minerals in the Portage Lake Lava Series

It is immediately apparent in studying the amygdule minerals in the Portage Lake lava series that there is wide variety in the kind and amount of the minerals present at different localities. Several attempts to make order out of this apparent chaos and to discover a regional pattern have been made. Broderick, Hohl, and Eidemiller (10, p. 694–705), in a review of the recent work of the Calumet and Hecla staff, describe mineral zoning curves based largely on the occurrence of chalcocite. In the same paper there are many pertinent observations regarding silicate mineral distribution, which supplement Broderick's earlier zoning study (7). It was concluded ". . . there may be a regional zoning related in some way to the copper deposits. . . . For the present the picture is by no means clear." The stimulation derived from the Calumet and Hecla studies was an effective incentive to attempt this regional synthesis of mineralogical data.

A map of an intensively prospected area, which includes the largest mines of the Michigan copper district, forms the base for Figures 5 and 6. Figure 5 shows the distribution of epidote and prehnite, and Figure 6 shows the distribution of microcline, quartz, and copper in relation to the mines. All information regarding the mineralogy of a single flow top or conglomerate hori-

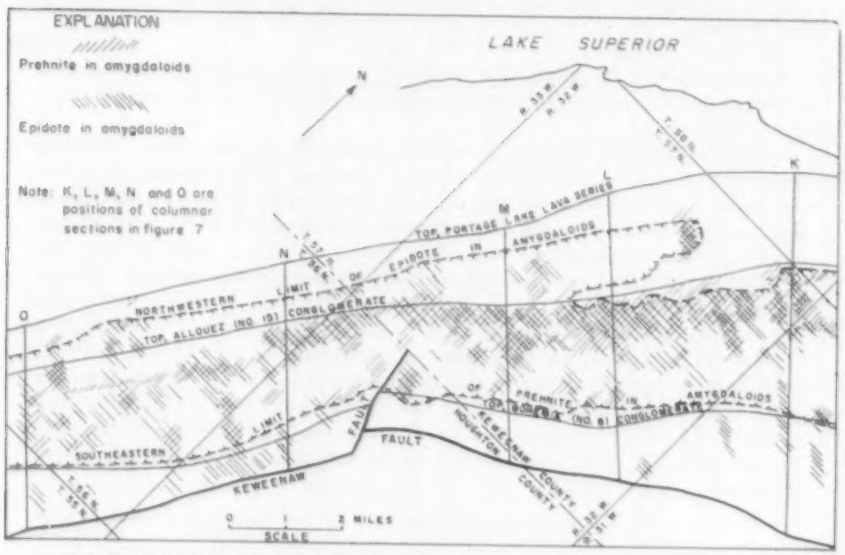


FIG. 5. Distribution of epidote and prehnite in amygdaloidal flow tops of the Portage Lake lava series in Townships 56 and 57 North.

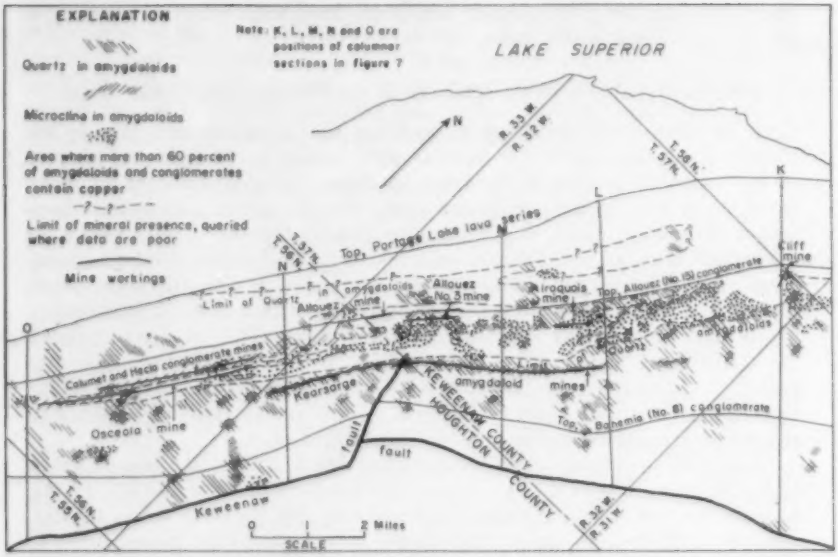


FIG. 6. Relationship of mines to distributions of copper, quartz, and microcline in amygdaloidal flow tops of the Portage Lake lava series in Townships 56 and 57 North.

zon was plotted at the location of the surface outcrop, though the information actually comes from many different depths up to, and in a few cases exceeding, 2,800 feet.

Epidote, prehnite, or quartz or more than one of these three minerals, together with calcite and chlorite occur in all types of amygdaloids, and with the possible exception of quartz, in the conglomerates of the Portage Lake lava series. There are only two exceptions of importance: 1) Part or the whole of some amygdaloids, commonly those containing detritus, have the amygdules and interfragmental spaces filled and some of the detritus replaced by calcite, laumontite, and chlorite. 2) A few thin and relatively impermeable flow tops contain only calcite and chlorite. If these exceptional mineralogical characteristics be ignored, then areas of occurrence, or zones,[3] based on the distribution of epidote, prehnite, and quartz may be outlined. These minerals prove to occur within limited areas in the Portage Lake lava series rather than in haphazard fashion (Figs. 5, 6, 7). These minerals are generally present in a great many, but not necessarily all, of the amygdaloids in their area of occurrence.

[3] The word "zone" will be used here in a somewhat different sense from its common usage in metamorphic petrology, where the zone named for a specific mineral may not be the only zone in which that mineral is stable. A zone as used here encompasses the smallest possible area that can be shown on the map scale employed, which encloses all occurrences of the mineral in the lava flow tops and conglomerates.

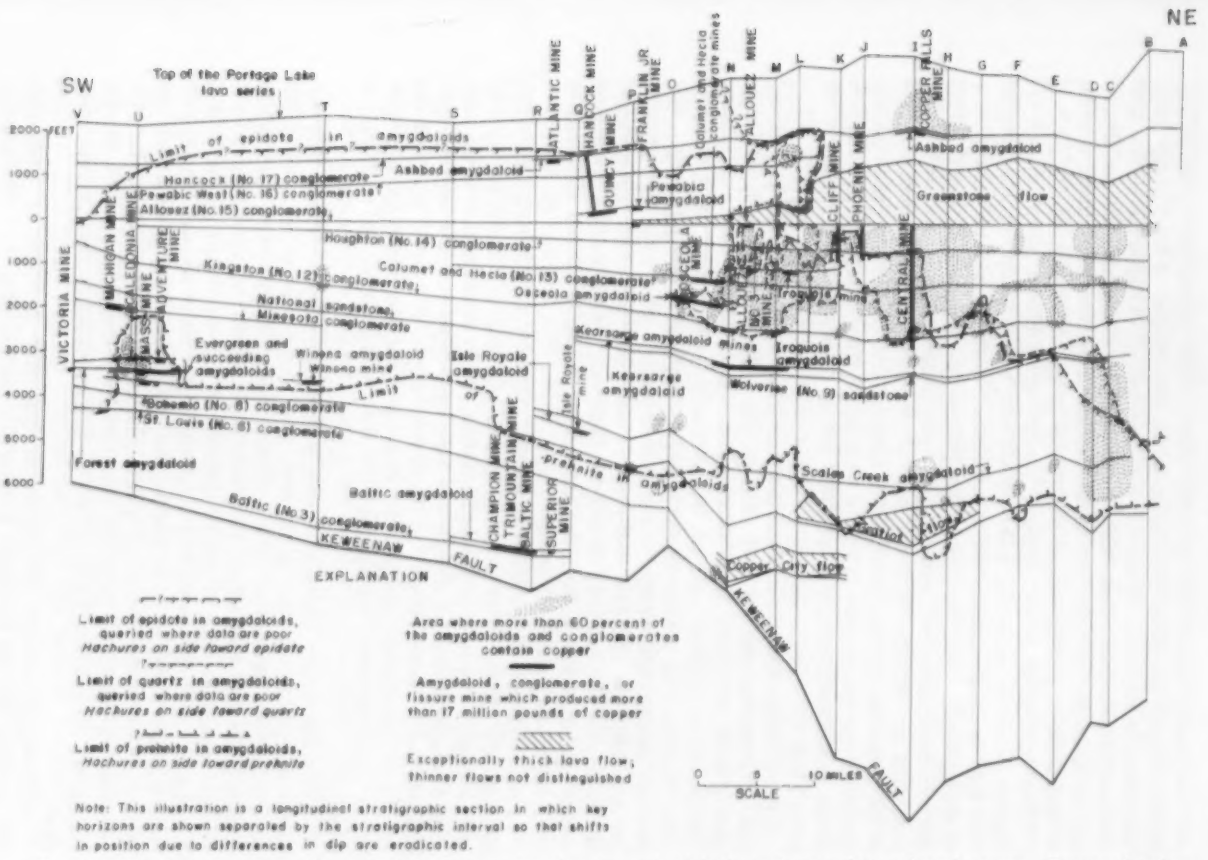


FIG. 7. Stratigraphy of the Portage Lake lava series showing mined beds and amygdule mineral zones. Prepared using stratigraphic sections by Butler and Burbank (13) and those accompanying geologic quadrangle maps of the area (18, 19, 20, 21, 25, 26, 53, 54, 56).

The quartz, epidote, and prehnite zones, major mines and areas of significant copper, are shown in relation to the stratigraphy of the Portage Lake lava series in Figure 7. Figure 7 is a longitudinal stratigraphic section that may be considered as a distorted map in which strike changes are not shown, and in which key horizons are shown separated by the stratigraphic interval so that shifts in position due to differences in dip are eradicated.

The boundaries of the epidote, quartz, and prehnite zones, though irregular in detail, generally follow thick and well-fragmented amygdaloidal flow tops or conglomerates for a considerable distance and then jump to a stratigraphically lower horizon as one follows the boundary eastward across the area represented in Figure 7. The quartz and epidote zones are roughly coincident and include the lower part of the series in the northeastern end of the peninsula and the entire series farther to the southwest, although the margin of the quartz zone is highly irregular in some places. The boundary of the quartz zone crosses about 7,000 feet of the stratigraphic section in 30 miles (Fig. 7).

The southern boundary of the prehnite zone lies in the lower part of the lava series throughout the peninsula and the zone therefore overlaps a large part of both the quartz and epidote zones. Most of the flow tops lacking prehnite in the prehnite zone are within that part of the zone which overlaps either the quartz or epidote zones, or both. Prehnite is rarely lacking in the prehnite zone outside the quartz and epidote zones. Flow tops with prehnite are therefore most abundant in the middle and upper part of the stratigraphic section toward the northeast end of the peninsula. Prehnite is less common to the southwest and in the lower part of the section, and does not occur at all in the lowest part of the section.

Pumpellyite in amygdules is found probably only within the quartz zone, although our data on this point are not as complete as for epidote, quartz, and prehnite. No zone of pumpellyitization and/or epidotization of the rock mass has been delineated, though it is quite clear from our data that this type of alteration is limited largely to the epidote zone. It is clear also that the amount of epidotization and pumpellyitization in the flow tops is much greater in the tops well within the epidote zone than in those near the epidote zone boundary.

Microcline occurs typically in only a single amygdaloid or in a few adjacent amygdaloids in any given area, and is not present in most of the amygdaloids, in contrast to quartz, epidote, and prehnite, which are present in almost all flow tops within their respective zones. Microcline commonly persists along the strike of one amygdaloid or a group of amygdaloids for a distance of a few miles or less. Amygdaloids just above or below a conglomerate bed are likely to carry microcline. Microcline-bearing flow tops are found throughout the series but, as sampled by drill holes, they are far outnumbered by flow tops in which microcline is absent. This spotty though widespread distribution (Fig. 6) makes it impractical to chart a microcline zone.

Soda-bearing zeolites are present in important quantities in rocks that crop out near the east tip of the Keweenaw peninsula (Fig. 1). The mineral

assemblage includes laumontite, natrolite, thomsonite, analcite and some chabazite (21, 25). Chalcedony, agate, chlorite and laumontite and calcite are present in many exposures and prehnite in a few. Although thomsonite, and less commonly natrolite are present in other Keweenaw localities, these minerals occur here as major mineral constituents of the flow tops. Perhaps, as suggested by Cornwall (oral communication) this area is all that is now exposed of a zone of soda zeolites. This small coastal strip has not been indicated on the stratigraphic section (Fig. 7).

Laumontite, calcite, and chlorite are so widespread that no zone boundaries are recognized within the area under consideration. Laumontite is more commonly present throughout the flow top in flows in the upper part of the stratigraphic section than in flows lower in the section.

Copper also shows a limited areal distribution if certain semiquantitative aspects of its occurrence are taken into consideration. Copper distribution is indicated in Figures 6 and 7 by two kinds of data: 1) occurrences in which copper is sufficiently rich to encourage underground exploration or mining; 2) places where megascopic copper is present in 60 percent or more of the flow tops and conglomerates. The former type of data are provided by mines, the latter from drill core. The percentage of occurrence of copper in flow tops and conglomerates was computed in the following manner for all areas in which diamond drill records were available. For each 400-foot interval of core in a given drill hole the number of copper-bearing amygdaloids was divided by the total number of tops in the interval. Amygdaloid tops with exceptional amounts of copper were given extra weight by doubling them in the numerator but not in the denominator. These quotients, expressed as percentages, were then projected up the dip of the beds to the surface for plotting on the map (Fig. 6) or plotted at the centers of the intervals on the stratigraphic sections (Fig. 7). The percentage values were then contoured and areas within the 60-percent contour were arbitrarily selected as "areas of significant copper." Where adjacent drill holes are collared in different stratigraphic horizons, and in heavily drilled areas, the copper distribution is quite accurate and consistent (i.e., most of area shown in Fig. 6). The copper distribution in areas of less drilling or where all the drill holes are collared at approximately the same horizon is likely to be somewhat less accurate because of the arbitrary choice of 400 feet as the sampling interval.

Most of the mines might be said to lie in two major areas or belts, one in the Evergreen and succeeding amygdaloids in the southern part of the peninsula, and another area, involving a larger part of the stratigraphy, extending from the Quincy mine to the Kearsarge amygdaloid mines (Fig. 7). There are, outside the two areas mentioned, the mines of the Baltic amygdaloid and of the Isle Royale amygdaloid. The areas of significant copper are not coincident with the Quincy-Kearsarge area of mines nor are amygdaloids adjacent to the more important mines characteristically in areas of significant copper. It is clear from the original data that this lack of correlation of mines with the areas of significant copper cannot be ascribed primarily to lack of information, even though there are commonly fewer drill holes in the

TABLE 1

MINERALS REPORTED FROM THE AMYGDULES OF THE LAVAS OF KEWEENAWAN AGE OF LAKE SUPERIOR DISTRICT EXCLUSIVE OF THE KEWEENAW PENINSULA

Locality (numbers refer to localities shown on Fig. 1)	Epidote	Quartz	Prehnite	Chlorite	Calcite	Laumontite	Copper	Other	Remarks	Sources of information
Weyerhauser, Wis. (1)	X	X	X	X	X	X	X			H. R. Cornwall (written communication)
Chippewa prospect and area near Wentworth, Wis. (2)	X	X	X	X	X	X	X			H. R. Cornwall (written communication) (28, p. 27–44)
Taylors Falls and vicinity, Minn. (3)	X	X	X	X	X	X	X	Red feldspar	Prehnite noted in two localities	(5) (28, p. 27–44)
Pine City, Minn. (4)		X		X	X	X		Analcite, datolite, orthoclase	Three analyses of chlorite (var. delessite, 29) quartz locally abundant	(29, 30)
Duluth, Minn. (5)	X	X	X	X	X		X	Red feldspar	Pyroxene, biotite, plagioclase and apatite are contact-metamorphic products (46, p. 1219–1220)	(46), Observations of senior author
Northwest shore of Lake Superior, Minn. (6)	X		X	X	X	X	X	Agate, thomsonite	Prehnite, containing copper, occurs locally, as at Knife River. Local concentrations of epidote seem to be related to intrusives. Rare quartz	(45, p. 816, 817), observations of senior author

TABLE 1—(*Continued*)

Locality (numbers refer to localities shown on Fig. 1)	Epidote	Quartz	Prehnite	Chlorite	Calcite	Laumontite	Copper	Other	Remarks	Sources of information
Isle Royale: Amygdaloid Island, Minong mine, and north shore area (7)	X	X	X	X	X	X	X	Analcite, pumpellyite, agate, adularia, datolite		H. R. Cornwall and W. S. White (oral communication), (35, p. 4–10, 57–96)
Isle Royale: Chippewa Harbor, Scoville Point, Southeast shore (8)	X	X	X	X	X	X	X	Pumpellyite, thomsonite		H. R. Cornwall and W. S. White (oral communication), 35, 4–20)
Edward Island Thunder Bay Thunder Cape (9)		X		X	X	X	X	Agate	Other unidentified zeolites	(49, p. 61)
Thunder Bay (10)	X	X	X	X	X	X	X	Agate	Mesolite, heulandite stilbite	(40, p. 71)
Michipicoten Island, Ontario (11)		X	X	X	X		X	Red feldspar, agate, amethyst	Radial zeolite also mentioned	(12, p. 17, 19, 36, 37)
Mamainse, Ontario (12)	X	X	X	X	X	X	X	Agate, datolite, thomsonite, mesolite	Prehnite in upper part of sequence; quartz and epidote in lower part	(37)

ground immediately surrounding mined areas than in the area of significant copper as a whole. Most of the areas of significant copper lie near the middle of the stratigraphic sequence and toward the northeastern end of the peninsula. These areas cross the stratigraphy only to a minor extent and die out to the southwest toward the Quincy-Kearsarge area of important mines. Other isolated areas of significant copper are found, one of which is coincident with the Mass-Adventure mines of the Evergreen and succeeding flows in the southwestern part of the district.

Relationship of Copper Occurrence to the Mineral Zones

There appear to be two relationships between mines, areas of significant copper, and the epidote, quartz, and prehnite zones. One, a very general relationship, is that the mines are all within the epidote zone. A second relationship suggested by the map (Fig. 6) and especially by the section (Fig. 7) is that copper is prevalent near the margin of the zone in which quartz occurs. This relationship is suggested by the location of the productive mines on the Calumet and Hecla (No. 13) conglomerate, and the Osceola and Kearsarge amygdaloids. The less productive Allouez mine, Allouez No. 3 mine, and the Iroquois mine are also located near the margin of the quartz zone. The Quincy mine may also lie near the quartz-zone margin. The margin of the quartz zone, now eroded, may lie a short way up dip from the Quincy workings, for the deeper workings are probably more quartz-rich than the shallow workings; this is strongly suggested by study of the mineralogy of amygdaloidal rock on mine dumps. The largest areas of significant copper lie generally northeast of the Quincy-Kearsarge belt of mines. They trend rudely parallel to and are also near, though generally outside, the quartz zone. Together, in a broad way, many of the mines and most of the areas of significant copper coincide with the limit of the quartz zone throughout much of the Portage Lake lava series. The important Isle Royale, Baltic amygdaloid, and Atlantic mines, and some lesser productive mines, such as the mines of the Evergreen and succeeding amygdaloids, are not significantly near or apparently related to the regional quartz-zone boundary; several small areas of significant copper also seem unrelated to this boundary.

Minerals in Amygdaloids of Lake Superior Flows of Keweenawan Age Outside of the Michigan Copper District

The minerals in the amygdaloids of lavas of Keweenawan age in the Lake Superior region as a whole are similar to those in the lavas of the Michigan Copper district as shown in Table 1. No minerals are reported from the amygdules of the Keweenawan lavas elsewhere in Lake Superior that are not found in the Michigan Copper district, with the exception of augite, plagioclase, biotite, and apatite, which are products of contact metamorphism of amygdule filling by the Duluth gabbro (46, p. 1219–1220). The mineralogy of each area is similar to one or several of the mineral zones of the Keweenaw peninsula. One notes, for example, the information from the 1907–1908 drilling in the flows at Mamainse, Ontario (37). Prehnite is reported only

in the flow tops of the upper part of the sequence and quartz and particularly epidote are reported only from the flow tops stratigraphically lower in the series. This is similar to the zoning in the Keweenaw peninsula and suggests that the quartz, epidote, and prehnite zone boundaries occur also in the Mamainse area. The information from the various areas listed in Table 1 suggests that several zones similar to those outlined in the Keweenaw Peninsula occur throughout the area of lava flows of the Keweenawan series of the Lake Superior basin.

Mineralogy of Amygdaloidal Rock on Mine Dumps

From Victoria to the end of the Keweenaw peninsula (Fig. 1), almost the only information on the mineralogy of the amygdaloids and conglomerates at many abandoned mines and prospects is from mine dumps, because of the inaccessibility of the workings. The dumps, consisting of rock discarded during mining operations, were examined at most of the old workings on the flow tops or conglomerates. Study of the mineralogy at one dump provides a composite sample of the amygdaloidal mineral assemblage in the workings tributary to the shaft; such samples from a series of dumps provide a running average of the mineralogy along the strike length represented by the underground workings, integrating the mineral assemblage throughout the depth of mining. In a few places the mineralogy of rock from a deep shaft can be compared with that from a shallow shaft, so that one gains some idea of the changes in mineralogy down the dip.

At dumps from workings in amygdaloids the percentage of each of the minerals in the amygdaloidal rock relative to the total amygdaloidal mineral content was estimated by two or more observers. The estimates for any one mineral usually differed by less than 10 percentage points.

Prehnite, quartz, calcite, and microcline are the minerals most common in the amygdaloids of the dumps. Rock containing only chlorite amygdules, though very common, was excluded from the estimates because the relative percent of chlorite, if this rock were included in the total, would depend on the extent to which the mine openings had penetrated footwall rock. Footwall rock includes both the stratigraphically lowest part of an amygdaloid and the upper part of the massive lava; it is sparsely amygdular and the amygdules are almost exclusively chlorite and minor calcite. Chlorite was recorded only where it was associated with the other common minerals. Laumontite is not properly represented in the quantitative estimates of the minerals found in the dump rock, because it weathers so easily that rocks containing it are largely disintegrated. A direct comparison was made between dump and underground estimates at one shaft (Seneca No. 3), which indicated that the dump estimates of mineralogy from rock on the waste dump and that exposed in the underground workings were satisfactory. Underground mapping shows that, as Broderick (10, p. 687–688) has suggested, there is no good correlation between abundance of copper and the amygdaloid mineralogy over distances of hundreds of feet. The fact that much copper-rich rock is not included in the dump sample does not therefore impair the

value of the dump estimate for correlation of amygdule mineralogy with mine richness. There were sufficient dumps on five of the seven important amygdaloids (Quincy, Osceola, Isle Royale, Kearsarge, and Baltic) to indicate variability in mineralogy. The dumps of the other two most important deposits (Atlantic and Calumet and Hecla (No. 13) conglomerate mines) provided little useful data, for many dumps at these shafts have been removed, or the rock from several shaft combined. On several other less productive amygdaloids there was also a series of shafts from which material was available for study of mineral variation along the strike.

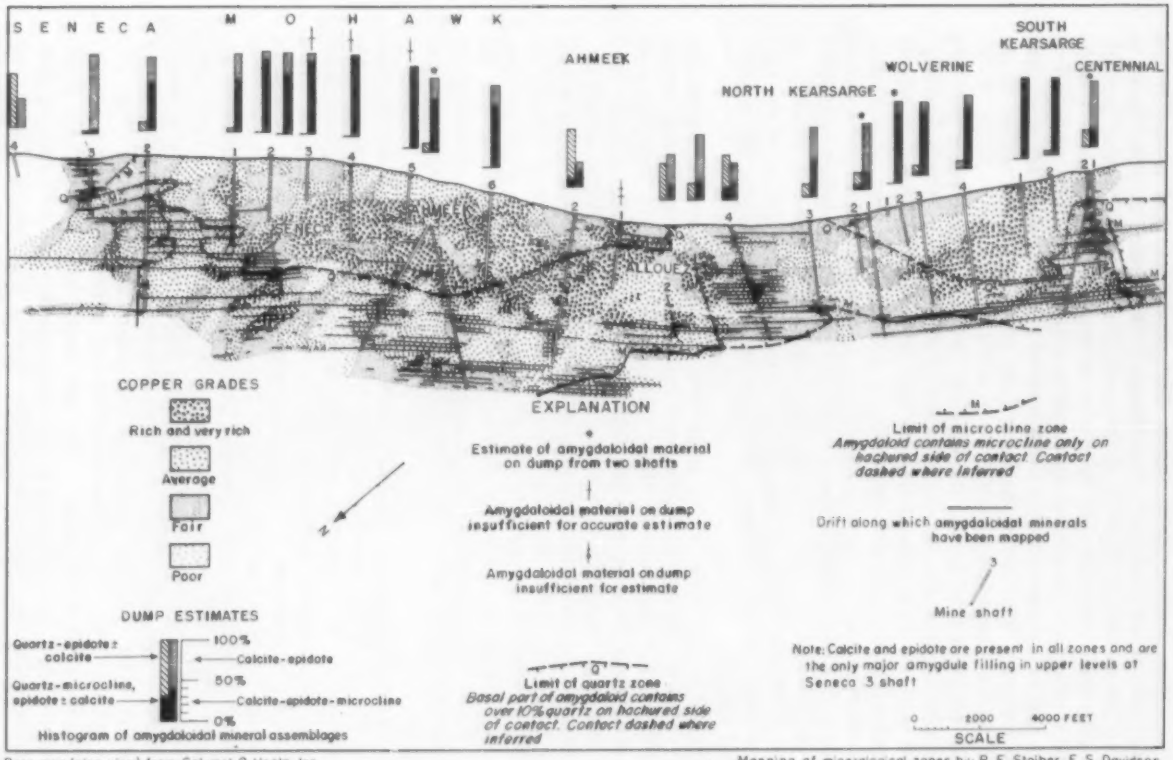
The writers hoped to find a mineral combination characteristic of shafts from which there was large production and another characteristic of shafts in poor ground, such as that proposed in 1883 by Irving (31, p. 185–186) who stated that an explorer looking for cupriferous belts should see "that one or more of the favorite associate minerals of the copper is present"—he calls epidote, prehnite, and chlorite "the favorite associates of the copper." The situation is not this simple. The presence or absence of no single mineral is important in itself, since several of the minerals, microcline, quartz, and prehnite are present or absent from some productive and some unproductive shafts. Epidote, to be sure, is always present in productive lodes but is also common where there is no production. The important difference between the productive mines and prospects seems to be the existence of a change in the amount of minerals such as quartz, prehnite, and microcline along strike or dip. In particular, our data indicate that the good mines with large or small production generally show, along strike or dip, a change in the relative percentages of quartz. Parts of several productive mines contain no quartz at all. Less quartz can in general be correlated with the more productive areas.

The generalizations regarding mineralogy of the copper occurrences gained from dump studies are compatible with the conclusions of the regional studies in suggesting that the border of the regional quartz zone is a favorable locus for copper concentrations. In addition, the dump studies from shafts such as those of the Baltic amygdaloid mines within the quartz zone emphasize the fact that there are areas of "no quartz" or "less quartz" within the quartz zone, and that copper concentrations may occur near the boundaries of these areas.

Mineralogy of the Mined Portion of the Kearsarge Amygdaloid

The Kearsarge amygdaloid was being mined at the time of this study along a strike length of 8 miles and to a vertical depth of 4,500 feet (Fig. 8). Dips range from over 40 degrees at the surface to 35 degrees at depth. Many shafts in the upper abandoned parts of the mined area were still partly accessible, permitting a more thorough coverage of the entire mined ground in this mine than in any other large mined area in the Michigan copper district.

The flow top in the mined area is, for the most part, a well-oxidized, very fragmental amygdaloid (Fig. 3A); the amygdaloidal portion has an average stratigraphic thickness between 6 and 7 feet, though it ranges up to 30 feet and in a few places has pinched out entirely (23).


S E N E C A
M O H A W K
AHMEEK
NORTH KEARSARGE
WOLVERINE
SOUTH KEARSARGE
CENTENNIAL
COPPER GRADES
Rich and very rich
Average
Fair
Poor
DUMP ESTIMATES
Quartz-epidote ± calcite
Quartz-microcline, epidote ± calcite
100%
Calcite-epidote
50%
Calcite-epidote-microcline
0%
Histogram of amygdaloidal mineral assemblages
EXPLANATION
Estimate of amygdaloidal material on dump from two shafts
Amygdaloidal material on dump insufficient for accurate estimate
Amygdaloidal material on dump insufficient for estimate
Limit of quartz zone
Basal part of amygdaloid contains over 10% quartz on hachured side of contact. Contact dashed where inferred
Limit of microcline zone
Amygdaloid contains microcline only on hachured side of contact. Contact dashed where inferred
Drift along which amygdaloidal minerals have been mapped
Mine shaft
Note: Calcite and epidote are present in all zones and are the only major amygdule filling in upper levels at Seneca 3 shaft
0 2000 4000 FEET
SCALE

Base map (plan view) from Calumet & Hecla, Inc.

Mapping of mineralogical zones by: R. E. Stoiber, E. S. Davidson, H. R. Cornwall, W. S. White, J. C. Wright.

Copper grade data from Calumet & Hecla Inc. records, compiled by W. S. White.

FIG. 8. Map showing distribution of amygdule minerals in Kearsarge amygdaloid mines and mine dumps.

Two types of rock, albite basalt, the major rock, and pumpellyitized basalt, occur in the flow top. Approximately 60 percent of albite basalt is euhedral albite feldspar laths in a fine-grained or cryptocrystalline groundmass. In some parts the groundmass is so crowded with hematite that its nature is obscure. In others, pyroxene grains together with opaque iron oxides and locally some chlorite and a cryptocrystalline matrix are interstitial to the feldspar. The amygdular base of the overlying flow is similar to the top of the Kearsarge flow.

The pumpellyitized part of the flow top (Fig. 2) is gray green and very brittle and contains abundant quartz and epidote in vesicles and interfragmental spaces. Thin sections indicate that the rock is composed largely of fine-grained pumpellyite that has replaced feldspar laths pseudomorphically. The intersertal material between the former feldspar laths contains anhedral pyroxene and unidentified material, probably pumpellyite, which is clouded with opaque iron oxides. The original structure, a mosaic of euhedral to subhedral feldspar laths, is very apparent in direct light because of the contrast between the black opaques of the intersertal material and the pumpellyitized feldspar.

The major minerals of the amygdules and interfragmental spaces are calcite, chlorite, microcline, quartz, and laumontite combined in the several assemblages described below. These minerals are sufficiently coarse grained that descriptions from megascopic examination are not ordinarily modified to an important degree by thin section study. Where examined in thin section, all of the apparently chlorite-pumpellyite-free mineral assemblages include pumpellyite and chlorite in minor amount; locally a few grains of twinned albite replace the rock adjacent to epidote-calcite fillings. The minor pumpellyite and chlorite is commonly overlooked or is indistinguishable and the albite is not distinguished on megascopic examination. The discussion on the following pages refers only to the obvious megascopic amygdular constituents.

Banding of Amygdule Mineral Assemblages.—Mapping of the distribution of the amygdule minerals revealed a hitherto unrecorded stratigraphic arrangement of these minerals from top to bottom of the amygdular layer formed by the Kearsarge amygdaloid and the base of the overlying flow. This stratigraphic arrangement of amygdule mineral assemblages in the Kearsarge amygdaloid is referred to collectively in this paper as banding—an individual assemblage is referred to as a band. These bands of amygdule mineral assemblages are rudely parallel to the plane of the flow and have remarkable continuity along the strike and dip. Five major bands of mineral assemblages are recognized. They are, from the lower part to the top of the amygdular layer: chlorite ± calcite ± microcline; quartz-epidote (Fig. 2); calcite-epidote (Fig. 3); calcite-microcline and generally epidote (Fig. 4); and chlorite-calcite ± microcline. The last named band is not in the Kearsarge amygdaloid, but is formed in the amygdular base of the overlying flow. The areas chosen for illustration of these banded assemblages (Fig. 9) are not the most ideal examples but illustrate the kinds of departure from the

idealized sequence that exist. One of the better underground exposures of all the mineral assemblages was seen on the 35th level of the Ahmeek mine, 399 to 500 feet south of No. 3 shaft (Fig. 9). The relative amounts of the amygdule minerals in the several bands and the degree of vesicle filling is shown in Table 2. Chemical analyses of the specimens are reported in a following section dealing with the origin of the amygdular minerals.

Banding of the amygdule mineral assemblages is least complete in the upper levels of the mines, where the quartz-epidote assemblage is rarely prominent, and in the intermediate levels. In the deeper levels, as for example, the bottom of the North Kearsarge shafts, the sequence, which includes the microcline amygdule assemblages and a thick quartz-epidote band, is re-

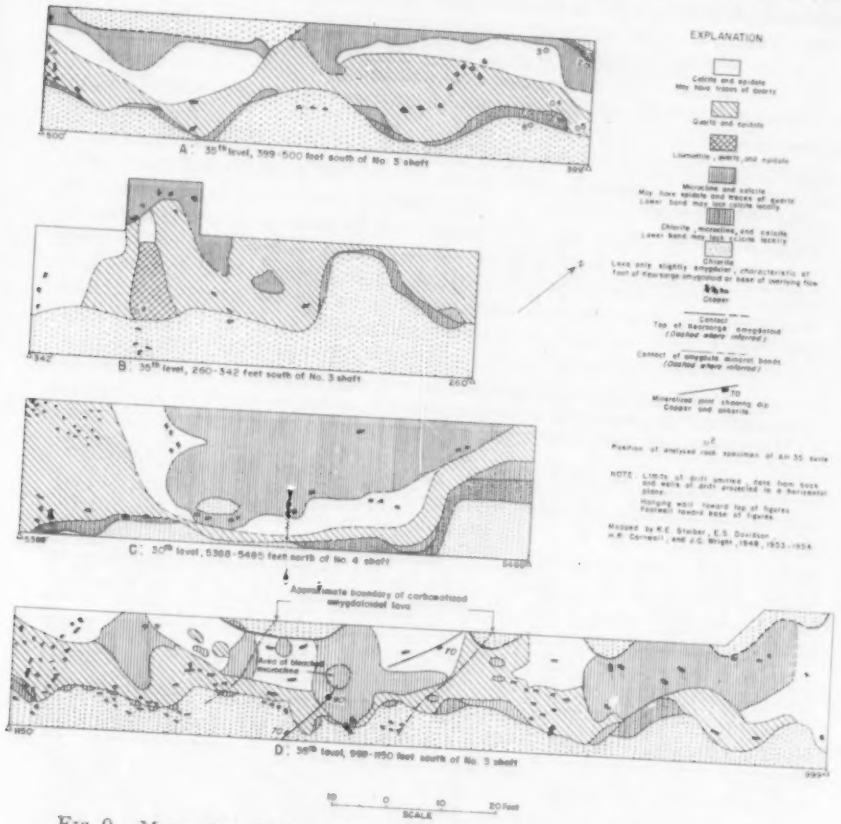

EXPLANATION
A: 35th level, 399-500 feet south of No. 3 shaft
B: 35th level, 260-342 feet south of No. 3 shaft
C: 30th level, 5388-5485 feet north of No. 4 shaft
Approximate boundary of carbonatized amygdaloidal lava
Area of bleached microcline
D: 35th level, 999-1150 feet south of No. 3 shaft
SCALE

FIG. 9. Maps of the 30th and 35th levels of the Ahmeek mine showing banding of amygdule mineral assemblages, Kearsarge amygdaloid, Houghton County, Michigan.

markably complete and representative of the ideal sequence; in places the bands extend with equal stratigraphic thickness for over a thousand feet along the strike. Any one of the three assemblages in the central portion of the amygdaloid may be absent or attain great width.

The limits of the mineral bands coincide approximately with changes in vesicular character of the flow top. Chlorite and generally calcite fill the amygdules in the sparsely amygdular basal portion of the flow top. Chlorite is much more abundant in this assemblage and is more easily recognized magascopically than in the succeeding assemblages. Where microcline is found in this assemblage it may be accompanied by epidote and commonly calcite in a narrow zone above the basal part of the amygdaloid (Fig. 9, especially A and C).

TABLE 2

VOLUME-PERCENT ESTIMATES OF AMYGDULE MINERALS IN AMYGDALOID SPECIMENS

Specimen number[1,2]	1	2	3	4	5	6	7	8	9
Volume of filled amygdules	4	19	40	15	7	25	33	12	35
Volume of void in imcompletely filled amygdules	0	1	0	2	11	0	0	0	0
Amygdule filling[3]									
Chlorite	74	3	0	0	0	0	69	100	
Microcline	15	45	0	0	0	82	25	0	
Calcite	5	47	87	0	1	0	0	Tr	
Epidote	0	5	12	96	90	10	1	0	45
Pumpellyite	6	Tr	Tr	0	0	0	0	0	
Quartz	0	0	1	4	9	8	5	0	47
Laumontite									8

[1] Chemical analyses of these samples are reported in Tables 4 and 5.
[2] Location of specimens shown in Figure 9 (A and B).
[3] Estimates are averages of independent estimates made by both authors.

In the lower part of the flow top, just above the sparsely amygdular portion, epidote lines the openings and quartz fills or partly fills the central part of the openings (Fig. 2). The groundmass of the flow top in the quartz-epidote band is pumpellyitized. In many parts of the ore deposit, especially up-dip from the limit of quartz (Fig. 8), the quartz-epidote assemblage is absent. In other parts of the ore deposit it extends high up in the flow top, in places nearly occupying the whole amygdaloid (Fig. 9, A, D).

The upper part of the flow top is commonly fragmental (Fig. 3) and the lava is typically brick red due to abundant inclusions of red hematite. Calcite and epidote are the major constituents of the amygdules and interfragmental filling (Fig. 3B), but just below the top of the flow and in the base of the overlying flow microcline may be present (Figs. 4, 9, especially A). In some areas microcline and calcite occur with quartz and epidote in the customary stratigraphic position of the quartz-epidote band. Locally, where microcline "floods" the whole amygdaloid, quartz is less abundant or is missing altogether.

Laumontite occurs in patches that extend from a few feet to several hun-

dred feet along the strike and lies almost always in the quartz-epidote band or the calcite-epidote band.

Prehnite is not known in the mined portion of the Kearsarge flow top in large quantities, though it is found in small amounts at the northeastern end of the mined area in the calcite-epidote assemblage.

The minerals adularia, gypsum, prehnite, native silver, copper, and chalcocite are present locally in small vugs or cavities and occur with no apparent regard to the several banded assemblages. Saponite is not uncommon in the southwestern half of the mined area but its detailed distribution is unknown.

The banding of the amygdule mineral assemblages is believed to be the result of hydrothermal deposition of these minerals along a permeable channel, the flow top. The banded arrangement may be explained in a general way by assuming that the feldspar and chlorite were deposited earliest and also farthest from the main solution channel, that quartz and epidote were deposited in the center of the channel, and that calcite filled the remaining openings later.

No correlation between banding and the ubiquitous distribution of copper (Fig. 9) or the grade of the copper ore has been discovered. This upholds the contention of Butler and Burbank (13, p. 149) that "in the later states of development, observation of the copper itself is a better indication of the grade of the ground than a study of the gangue minerals."

Zoning of Minerals with Depth and its Correlation with Copper.—In presenting the over-all results of the underground mineral mapping of the Kearsarge mines (Fig. 8), a simple mineralogical subdivision was adopted that could be extrapolated to areas of no data with some confidence and in which the observations of others and the observations from dumps could be incorporated. Two areas, or zones, are delineated on Figure 8; a zone in which microcline is present, and a zone in which quartz makes up more than 10 percent of the amygdular and interfragmental minerals of the quartz-epidote band in the lower part of the flow top. Exposures in the accessible deeper drifts, pillars near abandoned shafts and notes of earlier workers, all provided data.

Quartz content within the quartz zone increases down dip. This increase is not regular and detailed quantitative data are not available. The average quartz content of the whole amygdaloid within the quartz zone is probably about 15 percent. Outside of the quartz zone, the entire flow top contains considerably less than 10 percent quartz and in a great many places contains none. Microcline is most abundant near the surface and decreases irregularly in quantity with depth. The limit of microcline in depth has been reached along about one half the strike length mined, but lies below the limit of mining elsewhere. The microcline and quartz zone boundaries are roughly parallel; if this parallelism continues in areas in which the microcline limit is not yet reached by mining, the microcline boundary will be reached a few hundred feet beyond the present depth. The microcline and quartz zone boundaries follow the dip and are nearer together and more nearly coincident in the northeastern extremity of the mined area than in any other part.

A generalized map showing the relative abundance of copper was prepared by W. S. White from company reports giving estimates of grade by mine captains. These data are superimposed on the map of mineralogical zones (Fig. 8).

Copper values are much more irregular in distribution than the mineral zones, but at least two possible relationships between the abundance of copper and the quartz and microcline zones may be suggested. As one possibility, the limit of the microcline zone may be the approximate limit of significant copper values and the richest copper lies up dip from the zone boundary. The presence of rich ore in the microcline-free area near Seneca No. 2 shaft does not favor this hypothesis. Another possibility is that the richest copper occurs near the boundary of the quartz zone. This is supported in general throughout the mined Kearsarge amygdaloid, but better values might be expected northeast of Seneca No. 3 shaft, at intermediate depths in North Kearsarge Nos. 1, 2, and 3 shafts, and southwest of the Centennial shafts. It is quite clear that areas of high quartz content at depth in the mined area do not contain rich ore. This negative correlation with quartz content is supported by the mineralogy of the rock dumps of the low-grade Ojibway and La Salle prospects on the Kearsarge amygdaloid, on either side of the present workings. Microcline-rich amygdaloid on the dumps at both Ojibway shafts to the northeast and on the La Salle No. 2 shaft dump to the southwest contains a high percentage of quartz, and copper values were poor. A correlation of rich copper with the quartz-zone margin seems more likely from the present data, than that copper values are related to the presence or absence of microcline. Because copper content is undoubtedly influenced by permeability of the channel and other physical features, detailed mineralogical correlation will be obscured by these factors. The amygdule mineral distribution may have been controlled in part by these same conditions, but most of the minerals appear slightly earlier than the copper, and the permeability may have been changed enough during deposition to cause a less than perfect correlation between copper values and mineralogical zones.

This conclusion, the correlation of copper with the quartz zone margin, is in harmony with the conclusion reached from the regional studies—that many mines and the areas of significant copper in flow tops and conglomerates lie at or near the quartz-zone boundary, or near the boundary, of an area deficient in quartz within the quartz zone. It is also of interest in connection with the regional study to note that the Kearsarge mines lie regionally within the prehnite and quartz zones (Figs. 5, 6) yet detailed study shows a quartz-zone margin within the workings and virtual absence of prehnite. This illustrates what the dump study suggests, namely, that there are quartz-free or prehnite-free islands within the quartz and prehnite zones; these islands cannot be adequately shown by relatively wide-spaced drill-core data and the resultant small scale of the regional map. If other factors are favorable, flow tops and conglomerates with higher copper content may be expected not only at the margin of the quartz zone but also at the margin of quartz-free or quartz-deficient areas within the quartz zone.

Cross-cutting Fissures in the Mined Part of the Kearsarge Amygdaloid.—

Large, steeply dipping, copper-bearing veins that strike nearly at right angles to the Kearsarge amygdaloid have been described in detail as "short circuiting fissures" by Broderick (8, p. 840–856). Some of these fissures have been explored for short distances into the hanging and foot-wall of the Kearsarge amygdaloid and several have yielded substantial amounts of mass copper where they cross the amygdaloid. Broderick has noted (8, p. 845; Fig. 3, p. 847) that these fissures are not persistent along the strike and probably are not very persistent in depth. The larger of these fissures, most common in the vicinity of the Seneca No. 1 and Mohawk shafts (Fig. 8), are shown on a map of the Kearsarge amygdaloid mine workings by Butler and Burbank (13, Pl. 40).

A concentration of fissures in the Mohawk and Seneca mine area shows no relationship to the zonal pattern; the swarm of fissures cuts across all mineralogic zones and banded assemblages, both grossly and in detail. Such deflections or irregularities as do occur in the boundaries of mineralogic zones do not seem attributable to the presence or abundance of fissures.

The major metallic minerals of the fissures are copper, some with high arsenic content, and one or more copper-arsenic minerals. The gangue minerals are carbonates and quartz, chlorite, and epidote. Many of the smaller fissures contain no megascopically visible metallic constituent. Most of the copper in one of the largest and most profitable fissures, the Mass fissure, is found within 500 feet of the intersection with the Kearsarge amygdaloid, although the fissure persists somewhat further. The copper content of the amygdaloid is less than normal in most places adjacent to the larger of these fissures (13, p. 117; 8, p. 848–850).

Alteration of the groundmass of the amygdaloidal wallrock adjacent to the fissures was recognized by Butler and Burbank and their colleagues (13, p. 201; 8, p. 845), though the amygdules of the altered rock were not discussed. The writers have made the additional observation that the amygdule fillings and the minerals in the interfragmental spaces have been quite generally replaced by ankerite near the larger fissures for tens of feet along the strike of the lode. The extent of alteration adjacent to a very small fissure is indicated in Figure 9 (section D) and an analysis of similar rock, with and without amygdule filling, is presented in Table 5 (analyses 2-24 and 2-24S). Microscopic study of some of the amygdules near the margin of an ankerite-alteration area in the Kearsarge amygdaloid shows that quartz and epidote, both minerals characteristic of the unaltered adjacent Kearsarge amygdaloid, are partly replaced by ankerite. The zonal-growth pattern of quartz is preserved in the anhedra of ankerite. More important than the evidence of thin sections is the megascopic evidence. Carbonate-filled vesicles in areas of the flow top where microcline was present in amygdules exhibit a narrow rim of unreplaced microcline, somewhat bleached by the removal of hematite.

Broderick has interpreted the fissure filling as earlier than the copper mineralization of the flow top (8, p. 850). But native copper has a consistent place in the sequence of amygdule-filling minerals, as is shown by the abundant paragenetic evidence (13, p. 53–55) for its general contemporaniety with the several amygdule minerals. Alteration of the Kearsarge

TABLE 3—INCLUSION THERMOMETRIC STUDIES OF QUARTZ AND CALCITE FROM THE KEARSARGE AMYGDALOID MINES

Sample	Mineral	Location	Vertical depth in feet below sea level	Feet down dip, below sea level	Number of inclusions[2]	Size of inclusions in mm[1]	Remarks	Range of temperature of filling, °C[1]	Average of temperature of filling, °C[1]	Median temperature of filling, °C
S1-400	Quartz	Seneca No. 1 27 level 400 feet north	950	1,718	6			227°–360°	303°	300
A4-130	Quartz	Ahmeek No. 4 22 level 130 feet north	1,195	2,025	5			286°–299°	294°	295
A4-300	Quartz	Ahmeek No. 4 28 level 300 feet north	1,475	2,637	8	0.01–0.2	Also 1 other, believed secondary 168° C.	282°–320°	310° (295° if low value included)	312
A4-5403	Quartz	Ahmeek No. 4 30 level 5,403 feet south	1,630	3,006	7	0.01–0.2		296°–325°	309°	310
A4-150B	Quartz	Ahmeek No. 4 35 level 150 feet north	2,100	3,657	11			250°–365°	322°	320
A3-4060	Quartz	Ahmeek No. 3 51 level 4,060 feet south	3,525	5,502	5	0.1–0.5	Also one other, very different 205° C.	339°–376°[2]	360°[2] (339° if low value included)	360
C-5715	Calcite	Centennial 23 level 5,715 feet south	205	350	11	0.01–0.05	Equidimensional in random orientation; some flat and angular, like a negative rhombohedron. Both types probably primary in origin	116°–157°	133°	133
A4-150A	Calcite	Ahmeek No. 4 35 level 150 feet north	2,100	3,657	15	0.01–0.05	Equidimensional in random distribution, possibly primary in origin	132°–152°	139°	140
					4		Irregularly shaped in branching, curving and intersecting planes. Probably secondary in origin	127°–130°	129°	

[1] All laboratory data determined by Donald H. Richter, U. S. Geological Survey.
[2] Decrepitation experiments on this sample indicates initial maximum decrepitation at 360° C.

amygdaloid adjacent to these fissures is later than the amygdule fillings, as shown above, so the fissure mineralization was apparently later, not earlier, than the copper of the amygdaloidal flow tops. The apparent restriction of copper in the fissures to the vicinity of their intersections with the amygdaloid is consistent with the hypothesis that the source of the copper in the fissures was preexisting copper in the flow top. If this is so, this also is an argument that the fissure filling is later.

Broderick proposed (8, p. 847) that short-circuiting fissures had introduced minerals of a deeper zone into the position where they are now found nearer the surface. It is thus implied that the copper in the fissures is practically the same age as the copper of the flow top or perhaps earlier, and (8, p. 851) that some of the copper-bearing solutions used these fissures as channelways during mineralization of the Kearsarge amygdaloid. The late age of the fissure filling, however, favors the hypothesis that the carbonate and arsenic of the veins is of a later age than the major copper mineralization of the flow top. It is our opinion that the minerals of these fissures are a late discordant phase, so they are not further considered in the mineralogical zoning picture that has been outlined for the Kearsarge flow top.

Temperature of Formation of Quartz and Calcite Amygdules.—Data regarding temperature of formation of amygdule fillings in the Kearsarge flow top, based on microscopic stage heating and descrepitation techniques, have been supplied by D. H. Richter (written communication, October 26, 1954). The interpretation of fluid-inclusion data is subject to question so that all the conclusions based on this line of investigation are necessarily tentative. The data available indicate that amygdule filling occurred after the flows had accumulated and had been tilted and that temperatures during deposition were considerably hotter than normal ground-water temperatures.

Heating of the partly filled liquid-vapor inclusions in quartz indicates a median filling temperature between 295° and 360° C and in calcite indicates an average filling temperature between 133° and 140° C (Table 3). These data have not been corrected for the rock pressure that existed when the amygdules were filled, and such corrections (33, p. 541) would in every case raise the filling temperatures. The gradient between the lowest median temperature, 295° C at 1,195 feet, and the highest median temperature, 360° C at 3,525 feet, is about 2.8° C per 100 feet. This is a much steeper gradient than that found at the present time in the Calumet and Hekla (No. 13) conglomerate mine, and than that in a drill hole in flows near the Baltic mine, where the gradient is about 0.6° C per 100 feet (6, p. 2). Median temperatures are generally higher for the deeper specimens. Because the apparent temperature of formation of quartz and possibly calcite increases with depth down the dip of this single flow top, it is believed that the amygdules were filled when the flow was tilted rather than soon after its outpouring on a horizontal or near-horizontal surface.

(*To be continued in next number.*)

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THE Ag_2S AND Ag_2Se TRANSITIONS AS GEOLOGIC THERMOMETERS[1]

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ABSTRACT

The pressure dependence of the argentite-acanthite (Ag_2S) and high-low naumannite (Ag_2Se) transitions has been studied beyond 1,000 atm. The inversion temperatures, 176° C and 128° C are both raised less than 10° C by an increase of pressure of 1,000 atm. The usefulness of the presence of argentite and of high-naumannite as indicators of certain minimum temperatures is therefore enhanced, especially in analyzed samples.

INTRODUCTION

WHILE there are quite a few transitions in the common sulfide minerals their use for geologic thermometry has been partly limited by the lack of information on the influence of both pressure and solid solution on the transformation temperature. The mineral argentite, the most common ore of silver, however, does occur quite pure and one might then expect that if the pressure effect were known a useful "thermometer" might be made available for setting limits on the supposed temperatures of certain ore-forming solutions. The terminology in this area of sulfide mineralogy is somewhat confusing and in the following the terms used are first re-defined:

Acanthite—a monoclinic form of Ag_2S, the stable form at room temperature. Actually *all* natural specimens of Ag_2S so far described are probably acanthite, a fact first recognized by Ramsdell in 1925 (1). In the earlier literature, however, acanthite has been restricted to those crystals showing a needle-like (or other non-isometric habit).

Argentite—the cubic variety of Ag_2S, is stable only above 176° C. In the laboratory argentite has never been preserved to room temperature, and likewise in nature the material usually called argentite exhibits gross cubic external morphology but is in fact the monoclinic acanthite. Hence, it is probably accurate to say that no argentite has ever been found in nature but only acanthite pseudomorphous after argentite. An exact parallel is to be found in the case of high and low quartz, high quartz being the equivalent of argentite.

Naumannite.—Earley (2) has correctly classified naumannite as the low or β-form of Ag_2Se stable at room temperature. Thus, α-naumannite corresponds to argentite and β-naumannite to acanthite. The structures of α-naumannite and argentite are quite analogous, but that of β-naumannite is of "low" symmetry but not the same as acanthite. Dana VIII (3) reports the

[1] Contribution No. 58-99, College of Mineral Industries, The Pennsylvania State University, University Park, Pennsylvania. Work supported by NSF Grant G-1000.

TABLE 1

DATA ON Ag_2S AND Ag_2Se TRANSITIONS

Substance	Inert	Pressure (atm ± 20 atm)	Temperature (° C ± 1° C)	
			Heating (° C)	Cooling (° C)
Ag_2Se	Ag_2S	1	128	128
		340	131	131
(Naumannite)		680	133	133
		952	134.5	135
		1,156	136	137
Ag_2S	Ag_2Se	1	176	172
		300	176.5	174
		560	178	176
		840	180	180
		1,225	181	180.5

Calibrant—AgI with the transition taken as 146.0° C.

occurrence of (β-)naumannite as cubes pseudomorphic after the α-form. There is no clearcut record of β-naumannite occurring with external morphologies of lower symmetry, although Earley's sample may be one.

Various temperatures are reported for the transition in Ag_2S ranging from 160–180° C. The definitive work on the system Ag-S is that of Kracek (4) who reports a temperature of 175° C for the argentite-acanthite transition. Values between 122° C and 130° C have been given for the atmospheric pressure transition in Ag_2Se (2).

Experimental.—In the present investigation the effect of pressure on the temperature of transformation in these two compounds has been studied by differential thermal analysis at elevated pressure. The apparatus has been described elsewhere (5). Ag_2S was made by bubbling H_2S through a solution of reagent grade $AgNO_3$ acidified with HNO_3. The precipitate was washed free of NO_3-ions and subsequently dried. The compound Ag_2Se was a C. P. grade chemical supplied by Fisher Scientific Company.

Results.—The results of the present study are contained in Tables 1 and 2. At atmospheric pressure Ag_2S as prepared was found to transform at

TABLE 2

THERMODYNAMIC PERAMETERS FOR Ag_2S AND Ag_2Se TRANSITIONS

Substance	$\frac{dp}{dT}$ (atm/°)	T (°k)	ΔV (cc/mole)	ΔH_{tr} (cals/mole)	
				Present work	Literature
Ag_2S	$\frac{1,224}{S}$	449	.57 (at 176° C)	1,524 ± 420	1,010
Ag_2Se	$\frac{1,115}{S}$	401	1.23 (at 128° C)	1,678 ± 230	1,610

176° C and Ag_2Se at 128° C, both on heating. The reactions recorded in the thermograms proceeded very smoothly and rapidly. Reproducibility was remarkably good and supercooling was negligible in the case of Ag_2Se. The effect of pressure on the transformation temperature in Ag_2S was found to be surprisingly small. Table 2 contains the volume change calculated for the transitions. For Ag_2S the volumes for both the high- and low-temperature modifications were calculated from lattice parameters reported in the literature (3–6). For Ag_2Se the unit cell, and thermal expansion of the high form are measured by determining the variation of the cubic cell edge with temperature above 131° C, from a series of high-temperature X-ray powder patterns. It was assumed that the thermal expansions of the low and high forms would be quite similar. Making this assumption the difference in volume in the low form between 128° C and room temperature was calculated. It was found to be approximately 1 percent. The density of the low-temperature form was determined with a pycnometer and found to be 8.14 ± 0.01 gm per cc. From these data it was possible to calculate the "instantaneous" volume change" at the transition temperatures of both Ag_2S and Ag_2Se. The heats of transition were calculated by using the Clapeyron relationship. All these values are included in Table 2. The error limits given include the errors in the different measurements that affect the quantities in the Clapeyron equation (5).

DISCUSSION AND CONCLUSIONS

The fact that the temperatures of these two transitions are so insensitive to pressure is a useful one. From Kracek's work the Ag : S stoichiometry is known not to affect the temperature very much. The main ions that can be in solid solution in these minerals are S^{2-} for Se^{2-} or vice versa and Cu^{+} for Ag^{+}. The effect of these has not been quantitatively measured as yet but is probably not drastic. Therefore, the presence of argentite or "cubic-habit" naumannite in ore specimens—where analysis shows these minerals to be relatively pure—can be taken to indicate minimum temperatures of formation of approximately 180° C and 130° C, respectively.

The type of change in the ionic arrangement in Ag_2S or Ag_2Se at this transition is not known but the high entropy of transformation (approximately 4 e.u.) for rapid transitions and the peculiar effects in sensitive thermal analysis apparatus at the transition temperature—would suggest at least a partial randomization of the Ag^{+} ions as in the 146° C transition in AgI.

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March 27, 1959

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STUDY OF THE DISTRIBUTION OF SOME GEOCHEMICAL DATA[1]

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ABSTRACT

An examination of geochemical data is made by statistical methods. Values are plotted on logarithmic probability paper. In most cases results suggest that more than one distribution may be present.

Examples and proposed interpretations are given for data for mineralization in rock and soil, for biogeochemical values, for iron in soil, and clay size material in soil.

It is suggested that such tests may be useful in exploration and in evaluation of some of the large amounts of collected geochemical data.

INTRODUCTION

AHRENS (1) has reported that the distribution of the concentrations of some elements in specific rock types is log-normal. This was determined by plotting concentration intervals of the element against the frequency of occurrence of values in each interval to obtain a distribution curve or histogram that had a skewed form, instead of the symmetrical bell-shaped form found in a normal arithmetic distribution.

In the course of geochemical work on rock and soil we have studied many sets of data to determine the form of the distribution, particularly with the view toward expanding the use of the data for prospecting purposes.

Such distributions can be readily examined by plotting on probability graph paper. On logarithmic probability graph paper a single log-normal distribution gives a single straight line. We found that the expected "straight" lines sometimes showed breaks. The breaks suggest that more than one log-normal distribution occurs in the data.

The method of presentation described can be applied to any type of geochemical data provided that a sufficient number of observations have been made.

THE METHOD OF TREATING THE DATA

The distribution of data can be determined by a histogram-type plot as illustrated by the solid and dashed lines of Figure 1 for normal and log-normal type distributions, respectively. A more readily interpreted plot can be obtained by use of probability paper (2).

In using this type of paper, the data are divided into a number of classes, and the number of values falling in each class is calculated as a cumulative

[1] Published with permission of the Research Department, The New Jersey Zinc Company (of Pa.), Palmerton, Pennsylvania.

percentage value. The latter are plotted on the abcissa, against the upper limit of each class, which is plotted on the ordinate of the probability graph paper. When data having a normal or arithmetic type distribution (solid line plot of Fig. 1) are plotted on the arithmetic probability paper (linear ordinate), or when log-normally distributed data are plotted on the logarithmic probability paper (logarithmic ordinate), a straight line results. The plotting of normally distributed data on the logarithmic paper, or of log-normally distributed data on arithmetic paper results in curved, rather than straight lines.

Figure 3 shows plots on arithmetic probability paper.[2] In plotting the geochemical data discussed later, it was found that in every case straight lines were obtained only on the logarithmic paper indicating log-normal distribution so all the remaining plots are on this type of probability paper.[3]

In some sets of data more than one distribution can occur, resulting in a double-peaked histogram when the data are plotted as in Figure 1 or in two intersecting straight lines with different slopes when probability paper is used (2). The plot on probability paper is the more sensitive for detecting double distributions.

The effect of two distributions occurring in a set of data is illustrated by the following theoretical example.

Large sets of random numbers are available in tables (3) in which the numbers are all from a single normal distribution having a fixed average and standard deviation.

The following sets of numbers were obtained using this table.[4]

A. A set of 300 numbers ($N = 300$), average (μ) = 0, standard deviation (σ) = 1
B. A set with $N = 100$, $\mu = 2$, $\sigma = 1$
C. A set with $N = 100$, $\mu = 4$, $\sigma = 1$.

The tabled values have an average of zero as in set A. The averages of sets B and C were changed from zero by adding + 2 to all values for set B and by adding + 4 to all values for set C.

A frequency distribution plot of each set is shown in Figure 2. The larger set of data shows the highest peak and the centers (average) of the smaller sets are displaced to the right indicating the higher average values. The positions of the solid straight lines A, B and C of Figure 3 represent the individual data sets of Figure 2 if cumulated and plotted on probability paper.

The large set (A) averaging less than the others might represent a background distribution of a metal occurring in any geological environment. Sets (B) and (C) are smaller sets and have average values that are greater than the background average. (Average values are at the 50% point.)

[2] Keuffel & Esser Co., 359-23, Probability Scale x 90 Division.
[3] Keuffel & Esser Co., 359-24, Probability x Logarithmic.
[4] The tables available are normal tables and not log-normal. Hence, our example differs in this respect from the case encountered in practice, as in fact it does in other respects also. The example is meant to be illustrative and it is felt that it serves adequately in this respect.

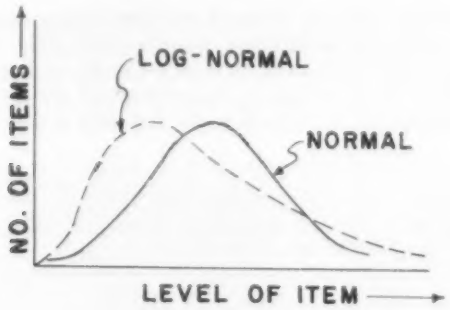


FIGURE 1. DISTRIBUTION CURVES

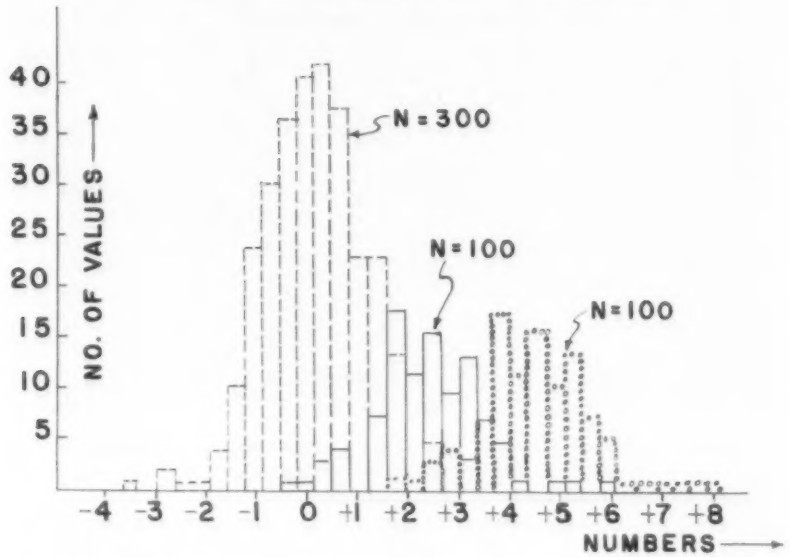


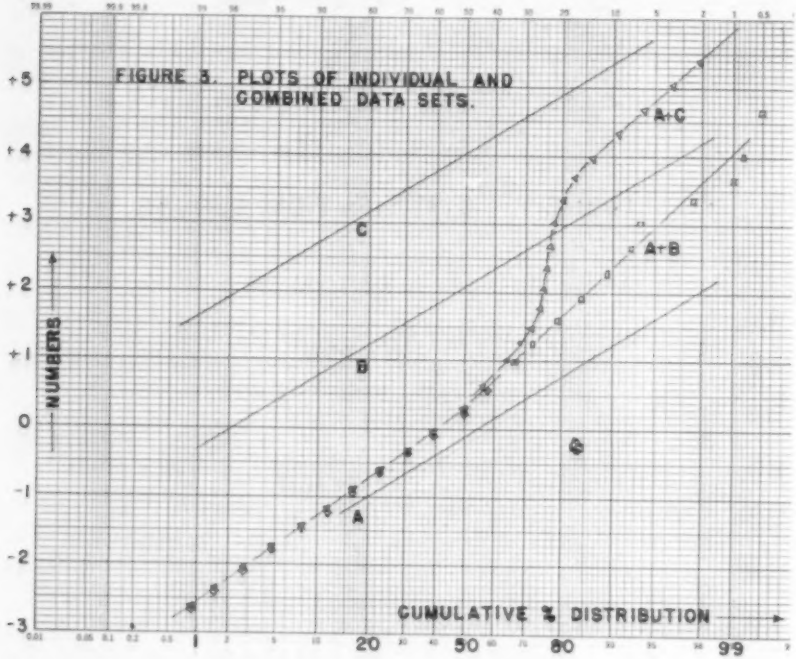
FIGURE 2. HISTOGRAMS OF DATA SETS

These data might represent two different sets of metal trace values occurring due to an ore formation process. The higher average values of the data would represent the increasing trace levels of metal expected in anomalous areas. The set with the highest average would represent anomalous metal values near ore and the set with the intermediate values would represent the anomalous distribution further from ore.

Also, the smaller set sizes (N = 100) would represent the smaller num-

ber of samples which might be obtained from anomalous areas as compared with the larger number of background samples (N = 300) expected.

In the practical application of trace analysis work, we hope we detect the B and C type sets (ore anomaly) in the presence of the type A set (background). In other words we have a set of data that is a summation of sets



A plus B or sets A plus C. The latter combination would represent the case nearer ore and the former the case further from ore since set C has a higher average than set B.

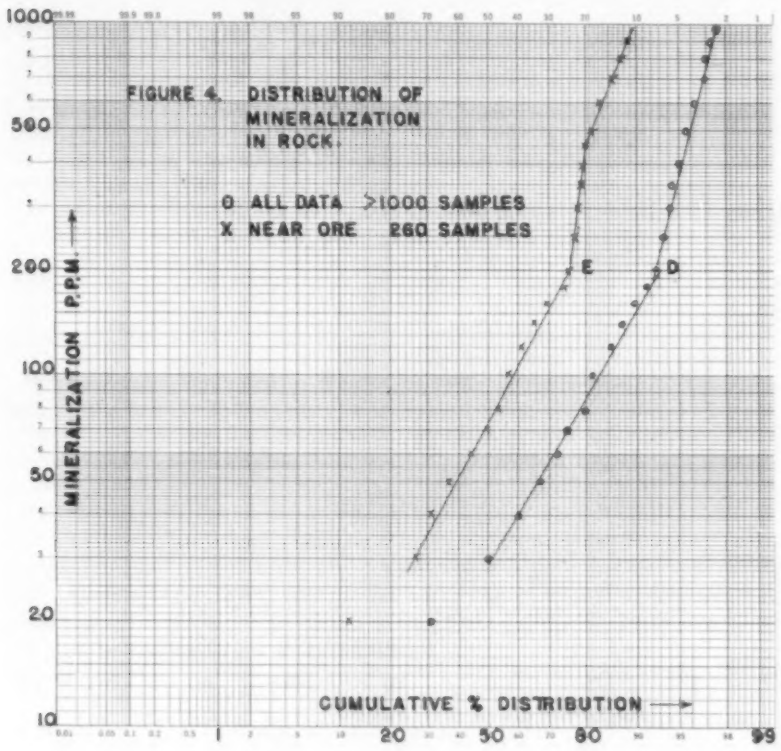
Hence, in our theoretical example we add the data of sets A and B, and of sets A and C, recalculate the cumulative per cent distribution and replot on Figure 3. The dashed curves have been drawn in to fit the plotted data.

Both the plots occurring in this theoretical example show departures from a straight line as might be expected due to the effects of summing the two sets. A minor upward trend at the higher percentages is noticed in the A plus B set, which becomes pronounced and develops into a curve that might be described as an "S" curve for the A plus C set.

MINERALIZATION VALUES IN ROCK

Over 1,000 dithizone analyses were available from diamond drill core in Franklin limestone surrounding the Franklin-Sterling ore deposits in Sus-

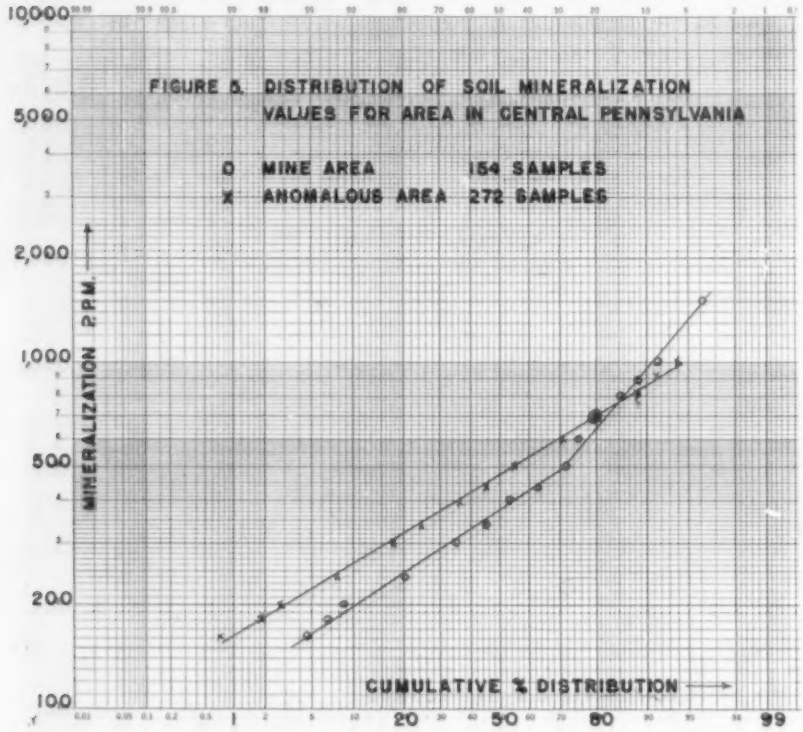
sex County, New Jersey. The dithizone method used on both rock and soil detects copper, lead, and zinc as an undifferentiated group and is reported as zinc equivalent and referred to as "mineralization" (4). The area geology and the minerals of the ore body have recently been described by Hague et al. (5) and by Metsger et al. (6). The samples analyzed were from core drilled



into country rock from the surface and from underground workings. Some of the surface cores were separated from known ore by distances up to one mile.

All the data from this area were cumulated and plotted and are shown as curve D of Figure 4. This curve shows a prominent break at 200 ppm. The curve is similar to the curve designated A + B of Figure 3. The small distinct break in this curve suggests that mineralization in the area is made up of a combination of two distributions. Recalling the hypothesis offered in developing the theoretical example, one would expect that a selection of analyses from core in the area near ore might show a break similar to that of

curve A + C of Figure 3. A group of 260 analyses from the area adjacent to known ore was plotted as curve E of Figure 4 and it is apparent that the break does become more prominent presumably due to the greater influence of the ore-forming processes on the mineralization of the area near ore.



MINERALIZATION VALUES IN SOIL

In the course of a geochemical exploration program many soil samples were collected in various areas of the Eastern United States and the mineralization values determined by dithizone titration (4). Values from some of the areas sampled were studied as described above to see if the mineralization content of the soil was log-normally distributed and if so, whether the data fell on a single straight line, or showed a break as was found for the rock values.

Figure 5 shows the logarithmic probability distribution plot of soil mineralization values for an area in central Pennsylvania on the northwestern edge of the Appalachian Mountain Belt that crosses the state. The rocks underlying the area were predominantly Ordovician dolomites. The soil in

an area of approximately 12 square miles was sampled at a 2-foot depth on a 500- × 500-foot grid. The average, or background amount of mineralization in the soil was about 250 ppm. Within this area two smaller areas of anomalous, or higher than average mineralization values were found, each area covering about 1 square mile.

These two adjacent areas, called the "Anomalous Area" and the "Mine Area" were similar in every respect, except that in the latter zinc and lead ore was known to exist in the dolomite, both from past mining activity and from more recent diamond drilling, whereas in the "Anomalous Area" diamond drilling did not disclose any ore, although a few, isolated shines of sphalerite and galena were found in the core. It is apparent from the plots that the points for the "Anomalous Area" can be represented very well by a single straight line, but for the "Mine Area" the points fall on two intersecting straight lines, with different slopes.

The occurrence of two straight lines in the data for soils from the "Mine Area" indicates that there are two distributions of mineralization in the soil, but in the "Anomalous Area," where the data can be represented by a single straight line, only one distribution is present. This suggests the possibility that there can be two distributions, or types, of mineralization in the soil, one representative of the normal or background amounts of soil mineralization, and another representing mineralization related to ore. In the "Anomalous Area" where no ore was found, only the background distribution occurs, but in the ore-bearing "Mine Area" the ore associated distribution is superimposed on the background distribution, resulting in two intersecting straight lines with different slopes.

DISCUSSION

The theoretical example and hypothesis developed above have been illustrated by practical examples using mineralization data in rock and in soil. The method of studying data appears to hold promise for application to practical prospecting problems in distinguishing significant anomalous values of a metal.

The procedure used in applying the method to a specific exploration project would have to be chosen to fit the local geological conditions such as soil and rock types, topography, faults, and previous knowledge of mineralization.

The examples that follow are included to indicate that a variety of geochemical data may be profitably examined by the method presented here.

It is felt that the recognition of such multiple distributions might be helpful in the further evaluation of some of the large amounts of geochemical data that have been collected.

BIOGEOCHEMICAL VALUES

In an area in the Champlain lowland of west-central Vermont, both the soil and the twigs of several species of trees were sampled around a zinc prospect occurring in slightly metamorphosed Cambro-Ordovician sediments, predominantly dolomites with some quartzites and phyllites.

The area sampled extended for some distance away from the known prospect so that many of the soil samples showed normal, or background amounts of mineralization (less than 200 ppm). Within this area were several locations where the soil showed high mineralization values (greater than 1,000 ppm). Twiggs from four species of trees were sampled in the same area as the soil sampling and analyzed for mineralization by the method developed by Warren (7).

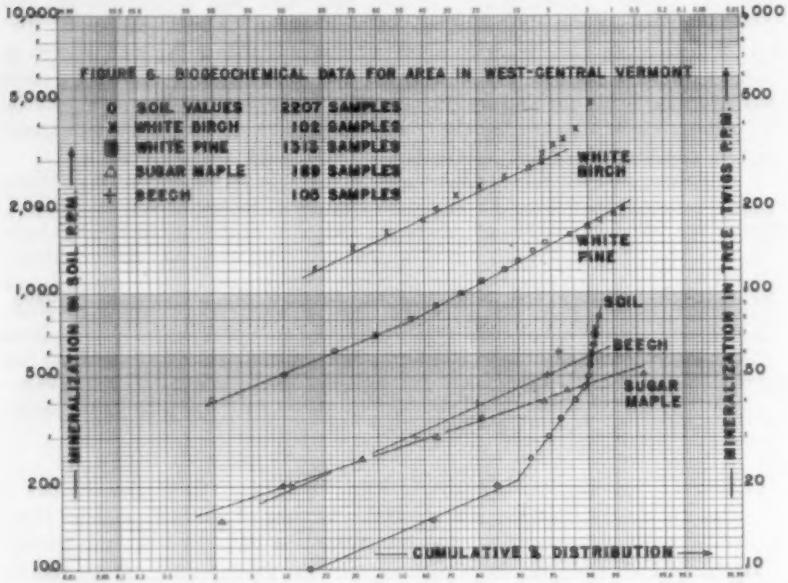


Figure 6 shows the results of plotting the data on logarithmic probability paper. The soil data can best be represented by three straight lines (the break above 97% may not be significant), but the tree values fall on single straight lines, with the exception of the white pine data, which show two lines, but with only slightly different slopes. This indicates that there is only one distribution of mineralization in the tree twigs, as compared with two, or more, in the soil.

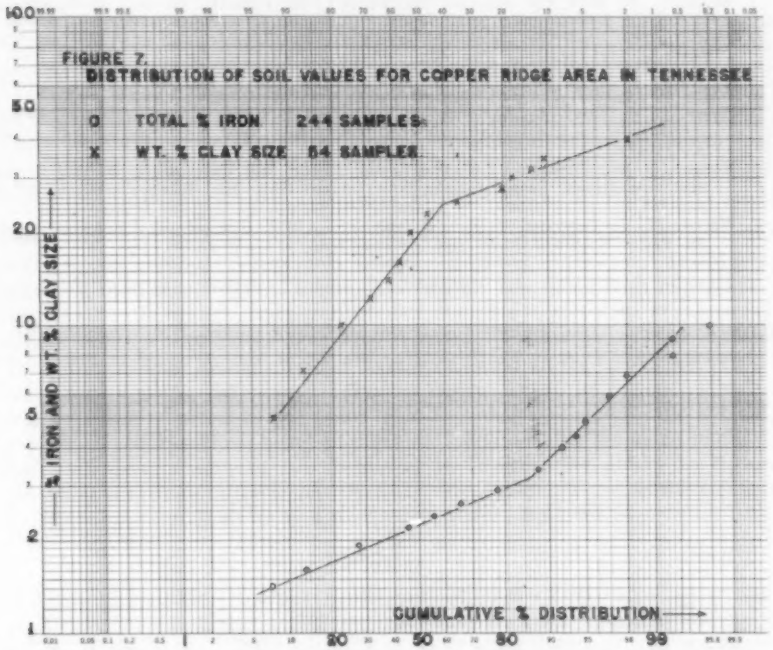
A possible explanation of this difference is that the tree is extracting from the soil only one form, or distribution, of mineralization. Previous work has shown that the soil mineralization is held in a relatively soluble form in the iron oxide and in a relatively insoluble form in the lattice of the clay minerals (4), so that the tree may be extracting only the more soluble form, showing, therefore, only a single distribution.

OTHER SOIL VALUES

In order to see if the distribution relations were peculiar to mineralization values, plots were made of some other data collected on soils. Two analyses

that were available were the total per cent iron, and the weight percent of clay size material in soils from the Copper Ridge area in Tennessee. The methods used for the analyses and a description of the area have been given previously (4).

Figure 7 shows the data for these two analyses plotted on logarithmic probability paper. Both plots show the data falling on two straight lines with different slopes. The weight percent clay size plot is unusual in that the top line has a lower slope than the bottom line.



Assuming that the presence of two straight lines with different slopes indicates two distributions, it is not difficult to postulate explanations.

For the total percent iron, it is possible that one distribution is due to residual iron and another to transported or illuviated iron, leached from the surface of the soil and precipitated at the present site. Two distributions for the clay-size material could result from the same process, or the distributions could result from the individual distributions of clay mineral and clay-size silica in the clay-size material.

These results indicate that double distributions may be quite common among various properties of soil and their detection might be of some help in a study of the characteristics or genesis of the soil.

ACKNOWLEDGMENT

We wish to thank all of our colleagues in the Exploration and Research Departments of The New Jersey Zinc Company who contributed in various ways to the work reported here.

NEW JERSEY ZINC CO.,
PALMERTON, PA.,
Feb. 18, 1959

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READILY EXTRACTABLE COPPER IN ERUPTIVE ROCKS AS A GUIDE FOR PROSPECTING

HARRY V. WARREN AND ROBERT E. DELAVAULT

ABSTRACT

This investigation explores the possibility of ascertaining the mineral potentialities of an area around an outcrop of limited size using rock analyses involving a chemical attack of moderate intensity. By using hot aqua regia, which does not substantially attack silicates, wide variations in the copper content of plutonic rocks have been noted.

In general, our preliminary results suggest that, in the vicinity of mineralization, the readily extractable copper of plutonic rocks is from five to ten times greater than that from rocks unrelated to mineralization. This technique may prove useful in exploration and prospecting.

INTRODUCTION

Until the present time, nearly all geochemical prospecting has involved searching for *secondary* dispersion haloes. However, *syngenetic* alterations have long been recognized as a feature commonly associated with mineralization. Curiously enough, comparatively few attempts to study the heavy metal content of syngenetic haloes have been reported. Furthermore, most studies on the heavy metal content of rocks have been based on the conception of the total metal content, determined either by spectroscopic or fusion methods. One opportunity for detecting some specific metal associated with a blind orebody, depends on there being a syngenetic halo involving the metal in question. Whatever theory of ore formation be favored, the ability to detect significant variations in the heavy metal content of country rock in the vicinity of mineralization is likely to be a useful aid in any search for ore.

HISTORY

Lovering and his associates (1948) and Riddell (1950) investigated the heavy metal content extractable by mild reagents from rocks in the near vicinity of ore bodies. The former used weak acetic solutions, and the latter dilute aqua regia. In both cases the amount of heavy metal extracted was small, the object being to avoid attacking the silicate rock minerals, some of which are known to contain appreciable copper within their crystal lattices.

In our opinion, the above workers opened up a promising line of attack which, to the best of our knowledge, deserves more attention than it appears to have received, and is worthy of further investigation.

GENERAL PROCEDURE

On the assumption that a heavy metal syngenetic halo would probably consist of sulphides, oxides, or silicates of these metals in discrete, although possibly invisible particles, a reagent able to attack drastically such com-

pounds has been employed, even at the risk of dissolving a little heavy metal from the principal rock-forming silicates.

The best solvent for the above purpose probably is aqua regia. As the results that follow show, only a small amount, a few parts per million, or less, of copper is extracted from plutonic rocks not associated with mineralization.

SAMPLING PROCEDURE

It is obviously impossible to sample a batholith or major rock formation in the same way that low-grade ore is sampled. This problem of sampling represents a study in itself. In order to diminish the risk of unwittingly selecting some exceptional portion of the rock formation we normally collect several specimens from well separated points.

Preparing a Sample for Analysis.—In an early stage of this investigation, selected chip samples of rock totalling a few ounces in weight, were crushed in a hydraulic press between steel plates covered by numerous layers of filter paper in order to reduce contamination. The broken up mixture of variously sized material was then quartered down to a few grams, which were crushed to a requisite degree of fineness in an agate mortar.

In order to deal with larger samples of rock, up to several pounds in weight, and to handle more effectively a greater number of samples, this slow and cumbersome method was replaced by mechanical grinding. We use a Bico "chipmunk" jaw crusher with ordinary steel plates for preliminary crushing. In practice no measurable amounts of copper are added by this machine. The material from this jaw crusher is then passed through a rotating grinder in which the grinding parts are made of alumina-magnesia ceramic plates, which cannot cause any addition of copper to the sample. By this means, samples are brought to millimeter or less particle size. Mixing and sampling for still finer grinding is now largely a matter of care.

In the earlier stages of this investigation, fine grinding was completed by hand in an agate or mullite mortar or an alumina-magnesia ceramic buckboard (3), with a muller of the same material. To prevent contamination, the buckboard and muller were cleaned by crushing a little of the rock that was about to be finely ground. At this stage ideally it would be desirable to check the fineness of the sample by means of a series of screens. However, in practice, unless the screens are small, non metallic, and used only once, there are the problems of the risk of losing some specific portions of the sample and of contamination. Fortunately, it is practical to assess the degree of fineness of a sample merely by its response when being ground on either buckboard or mortar.

From the supposed nature of the particles containing the copper, it is reasonable to expect that they would be localized at points of breakage, and that, if this were the case, then it should not be necessary to grind particularly finely to enable them to be chemically attacked. Experimental data, which are presented later in this paper, support the above conclusion. At all events, in this investigation, we have considered it sufficient to submit a few grams, carefully sampled, from the product of the ceramic grinder, for about ten

minutes treatment in a Spex "Mixer-Mill." The Spex Mixer-Mill is a high-speed ball mill made of a special alumina-magnesia ceramic with balls of the same material. The resulting rock powder is normally quite smooth, having a flour-like consistency and appearance.

Chemical Attack.—Two grams of finely ground rock are placed in a 20 ml pyrex beaker, and 2 ml of aqua regia added. The C.P. nitric acid must normally be redistilled and the C.P. hydrochloric checked to be sure that it contains only a tolerable amount of copper in relation to the content of the rock being investigated. Our hydrochloric acid contained less than 0.02 microgram of heavy metals per ml, expressed as zinc.

The beakers are placed at the edge of an electric heating plate, and pushed inwards far enough to heat for some 15 to 30 minutes before the aqua regia is evaporated. The residue is moistened with 0.5 ml of concentrated hydrochloric which is then evaporated in order to eliminate nitrous compounds. Then 4 drops of 50 percent hydrochloric are added, followed by 3–4 ml of water.

Some filters contain too much copper for determination in normal rocks: these filters must be placed on a funnel and treated with a few ml of 50 percent hydrochloric which, in turn, is washed off with water before use. By careful decanting and by washing sparingly, it is possible to obtain nearly all of the extracted metal in a volume of 20 ml.

Copper is determined colorimetrically using as a reagent biquinolyl (otherwise known as biquinoline or diquinoleine). Biquinolyl, under reducing conditions, gives a red complex of monovalent copper. The reagent is introduced as a solution in a small volume of amyl alcohol, into which the complex collects on shaking. The solution contains acetic acid and acetate in order to establish a low enough acidity, pH 5 or less acid, and citrate for keeping any ferric iron in solution until it is reduced to the ferrous state.

Biquinolyl is a little less sensitive than the better known dithizone, but it is not liable to interference even from large amounts of iron. Biquinolyl was introduced by Breckenridge, Lewis, and Quick (4) and applied to rock analysis by Almond (1).

Reagents.—(a) Ascorbic acid, copper free. Weigh ten mg into a small tube, and add an equivalent amount to each assay; no greater precision is needed. If copper free ascorbic acid is not available, use hydroxylamine hydrochloride, which may be added directly to the acetate-citrate solution.

(b) Acetate-citrate solution: 100 grams dibasic (acid) ammonium citrate, 100 grams sodium acetate, 20 ml acetic acid, plus water to make one liter. If this solution does not give satisfactory blanks with biquinolyl, it should be purified either with biquinolyl or dithizone. If no copper-free ascorbic acid is available add 50 grams of hydroxylamine hydrochloride.

(c) Biquinolyl solution: 20 mg in 100 ml of isoamyl or normal amyl alcohol.

(d) Ferric iron solution: 5 mg iron per ml copper free.

(e) Copper standard solution: 100 micrograms per ml. This solution should contain hydrochloric acid to make it I N in order that dilute solutions keep long enough for use.

COLORIMETRIC PROCEDURE

By diluting the copper solution, prepare in 15 × 125 mm pyrex test tubes, a series of standards ranging from 0.1 to 20 micrograms. To each standard add 2 ml of acetate-citrate solution, 2 drops ferric iron solution, and approximately 10 mg of ascorbic acid: Shake gently to mix the ingredients, and, with water, bring to a volume of about 8 ml. Introduce 1 ml of biquinolyl solution (only 0.5 ml into those standards below 0.5 mg). Close with an acid-washed cork or polyethylene stopper. Turn upside down and shake gently for about two minutes. Place right side up.

As has been stated, it is possible to replace ascorbic acid by hydroxylamine added to the acetate-citrate solution, but recovery of very small amounts of copper is not so good. Iron has a helpful catalytic action and recovery of copper in the standard is apt to be low if the chemicals are so pure that they contain negligible iron.

Into test tubes of the same size, add 2 ml of acetate-citrate solution and 10 mg of ascorbic acid to an aliquot of the rock extract. Five mls usually represents a satisfactory preliminary aliquot. Shake with 1.0 ml biquinolyl solu-

BACKGROUND CONTENTS OF EXTRACTABLE COPPER

Area of British Columbia	Rock type	Aqua regia soluble copper in parts per million	Formation no. on geological survey map	Reference
Batholithic Rocks from Supposedly Non-Mineralized Areas				
West Vancouver 1 A	Granodiorite	2	BH_2	Armstrong 1953
West Vancouver 1 B (Xenolith)	Basic inclusion	5	?	Armstrong 1953
West Vancouver 1 C	Granodiorite	4	BH_2	Armstrong 1953
Eagle Harbour	Granodiorite	1	Hb_2	Armstrong 1953
North Vancouver	Granite	1	H_1	Armstrong 1953
Chase	Granodiorite	1	14	Rice & Jones (1948)
Cousins Bay	Granite	1	15	Rice & Jones (1948)
Kettle River	Granite	1	12	Cairnes 1936
Lac Le Jeune	Quartz diorite	2	5	Cockfield (1944)
Rose Hill	Quartz diorite	2	5	Cockfield (1944)
Batholithic Rocks with Mineralization Nearby				
Kettle River	Quartz diorite	52	8	Cairnes 1936
Sugar Loaf Mountain	Diorite	60	5 (b)	
Sugar Loaf Mountain	Diorite	18	5 (b)	
Highland Valley Area	Guichon quartz diorite	120		White et al. 1951
Highland Valley Area	Bethsaida granodiorite	3		White et al. 1951
Highland Valley Area	Bethsaida granodiorite	20		White et al. 1951
Highland Valley Area	Bethsaida granodiorite	9		White et al. 1951
Highland Valley Area	Bethlehem quarta diorite	32, 20 110, 18 50, 45, 7		White et al. 1951

tion, unless a low content is expected when 0.5 ml may be used. The resulting supernatant layer may then be compared with the standards.

OKANAGAN INTRUSIVES

In the area northwest of Peachland there are a number of intrusives mapped by Cairnes (5) as Okanagan Intrusives. Just off this map area on the west lies Brenda Lake, where recently considerable exploration work has been carried on. Not wishing to prejudice any results we might obtain, Mr. C. Ney, of Northwestern Explorations, let us have a collection of samples illustrating the various types of intrusive rocks in the area. Our analyses of these rocks ran as follows, in parts per million Cu—1, 1.5, 3, 6, 6, 7, 7, 10, 28, 60, 300.

From the above it can readily be seen that most of the samples contain copper in amounts comparable with those reported from negative areas, but that at least three are anomalously high. For obvious reasons we have not yet been permitted to disclose the precise locality from which individual samples have come, but we have been assured by Mr. Ney that the copper-high samples come from intrusive rocks close to areas of known mineralization.

DISCUSSION OF RESULTS

Vinogradov (11) has summarized the results of investigations made on the total copper contents of various types of rocks. The results reported by all workers average as follows:

Basic Igneous	140 ppm
Medium Igneous	35 ppm
Acidic Igneous	30 ppm

Rankama and Sahama (8) give the following as being representative of the total copper content:

Acidic Igneous	15–16 ppm
Basic Igneous	30–149 ppm

Accepting the validity of the averages given above, it would appear useful to investigate variations between the readily extractable copper of rocks in mineralized areas and in non-mineralized areas. These variations might well prove to be of greater significance than variations in the total copper content of the corresponding rocks.

A glance at our table of background values shows that they represent only a small fraction of the total copper content of the various classes of rock listed above.

All rocks near mineralization do not necessarily contain high extractable copper. At Beaverdell a granite, which is younger and presumed to post-date the period of mineralization in this area, contains negligible extractable copper, 1 ppm, in contrast to the diorite, 52 ppm, which is believed to be associated with the mineralization: this is true even where the granite is much nearer than the diorite to known mineralization of ore grade.

It is interesting to note that the three granitic rocks classified as granite–

North Vancouver, Cousins Bay, and Beaverdell—all contain extremely low amounts of readily extractable copper, indeed in each case only 1 ppm. Contrariwise, quartz diorites not only contain all the highest amounts of readily extractable copper—Guichon quartz diorite 120 ppm, Bethlehem quartz diorite 110 ppm, Kettle River quartz diorite 52 ppm—but also possess in places comparatively little readily extractable copper—Lac Le Jeune Quartz Diorite 2 ppm, and Rose Hill Quartz Diorite 2 ppm.

Furthermore, mere proximity to disseminated copper mineralization in batholithic rocks does not necessarily lead to there being high extractable copper in contiguous plutonic rocks. Three samples were taken of an intrusive body, known locally as the Gump Lake intrusives, lying within a mile of outcropping Bethlehem quartz diorite. The Gump Lake intrusives have been given a field classification of quartz monzonite: the three samples ran 4, 1, and 1 ppm of readily extractable copper.

All in all, without in any way attempting to anticipate any ultimate conclusions, it would appear that studies of the readily extractable contents of copper in plutonic rocks might well lead to discoveries not only of significance in the determination of the genesis of some ore bodies, but also provide a geochemical prospecting tool of some value. Probably it would be wise to carry on a parallel study of the total copper contained in these rocks.

PREPARATION OF SAMPLES

If we accept the hypothesis that most of the readily extractable copper comes from heavy metal compounds crystallized in discrete particles, rather than dispersed in the lattice of the main rock-forming minerals, then it follows that, for analytical purposes, extremely fine grinding of samples may not be necessary. On the other hand, very small samples may not prove to be representative of a rock.

From rock N. 18, the one with 300 ppm of readily extractable copper, from the Okanagan Intrusive, two series of 0.05 gram samples were taken. One consisted of twelve samples of comparatively coarse material, 1 mm and under, taken directly from the ceramic grinder, and the other of ten samples of identical material which had been finely ground by hand on a ceramic buckboard.

The results were as follows in micrograms per 0.05 gram of sample.

(a) Coarsely ground. 7, 7, 8, 8, 9, 16, 18, 20, 22, 22, 23, 24.

Average for the above—15.2 micrograms, giving an average content of 304 ppm.

(b) Finely ground. 7, 9, 14, 14, 15, 16, 16, 17, 18, 18.

Average for the above—14.4 micrograms, giving an average content of 298 ppm.

From rock N.36, the one with 60 ppm of readily extractable copper, from the Okanagan Intrusive, ten 0.05 gram samples from material finely ground by hand were assayed. The results were as follows, expressed in micrograms of copper:

2.5, 2.5, 3, 3, 3, 3, 3.5, 3.5, 3.5, 3.5.

Average for the above—3.1 micrograms, giving an average value of 62 ppm.

The first and second sets of analyses given above support the hypothesis that the readily soluble copper comes from discrete particles rather than any general impregnation of mineral lattices. This suggests also that extremely fine grinding may not be necessary for the particular purpose of spotting anomalies. Even the lowest determination on N.18 would be equivalent to 140 ppm, and would not fail to draw attention to the anomalous character of this rock.

The point of the above discussion is to show that relatively small samples of comparatively coarse material, i.e., 1 mm and less, may be used to determine by simple chemical methods, anomalous quantities of copper in eruptive rocks.

Obviously many more investigations must be made before it will be prudent to draw any general conclusions as to the validity of the above technique.

ACKNOWLEDGMENTS

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Jan. 19, 1959

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"MAGNETIC" CHROMITE FROM SHOAL POND, NORTHEASTERN NEWFOUNDLAND[1]

STUART E. JENNESS

ABSTRACT

The magnetic property of the chromite at Shoal Pond, Newfoundland, is not inherent to the chromite, as formerly reported, but is caused by the presence of many tiny intersecting veinlets of magnetite within some of the chromite grains. Somewhat similar textures have been reported in Europe, but only one similar phenomenon has been described in North America.

A QUARTER of a century ago Snelgrove (7) reported the occurrence of magnetic chromite at Shoal Pond in northeastern Newfoundland. By means of an accompanying table he showed that its magnetic susceptibility greatly exceeded that of chromite from five other localities in Newfoundland. Although offering no explanation for this abnormal property, he suggested that it might prove a useful aid to chromite prospecting.

The present paper explains the cause of the magnetic property and draws attention to a chromite texture that is reportedly of common occurrence (Ramdohr, 1958, personal communication), but which has so far escaped mention in English language mineralogy texts (e.g., Dana (1); Edwards (2)).

A re-examination of the Shoal Pond deposit by the writer (4) revealed nothing geologically unusual about the chromite occurrence that would explain the magnetic property. The chromite is present as disseminated grains and small massive lenses in a typically lens-shaped, alpine-type serpentinite body, known as Chrome Hill, which measures about ½ mile long and 400 feet wide. The deposit lies at the northern end of a belt of ultrabasic rocks that crosses the eastern half of Newfoundland (Fig. 1). The enclosing rocks are steeply dipping phyllites, sandstones, and lavas of the Gander Lake group, of probable Ordovician age.

Fine crushing of selected specimens of the chromite from Chrome Hill yielded two distinct components, one a black strongly magnetic powder, which proved to be magnetite, the other a more abundant, chalky brown, non-magnetic powdered chromite. Other specimens from the same deposit were not magnetic, and yielded only the one component. Thus the supposed magnetic property of the Chrome Hill chromite is actually caused by the presence of small amounts of accompanying magnetite.

Examination of several polished specimens of the chromite showed that the magnetite occurs as microscopic veinlets in many of the grains of chromite (Figs. 2a, 2b). Seen under the reflecting microscope, the veinlets range

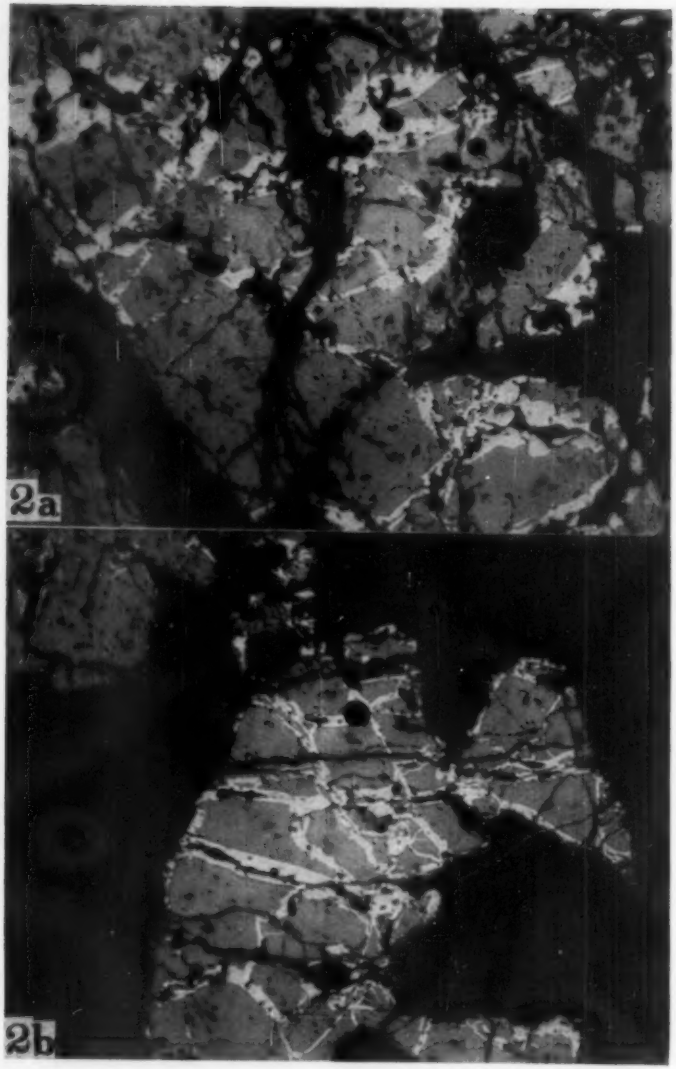
[1] Published by permission of the Director, Geological Survey of Canada, Department of Mines and Technical Surveys, Ottawa, Canada.

principally between 0.1 mm and 0.001 mm wide. Most of them are readily apparent under medium power magnification (95 ×), but some are barely visible even under high magnification (450 ×). The veinlets have subparallel to irregular walls and cut irregularly across the chromite showing no preference for crystallographic directions in that mineral. The magnetite thus is not an ex-solution phenomenon, but rather a fracture filling in the chromite, with some minor replacement at vein intersections. Some of the magnetite veinlets have in turn been fractured and veined by serpentine.

FIG. 1. Sketch map of Newfoundland showing the locations of Shoal Pond and the principal ultrabasic bodies (black patches) in the eastern part of the island.

A search of the literature has turned up only one published description of such a phenomenon elsewhere in North America, that of Kidd (5) in the Thunder Bay district of Ontario. His description and photograph of magnetite veins in chromite are almost identical to those of the writer. Furthermore, the geologic environment he describes resembles that at Shoal Pond, especially in (1) the local alteration of the ultrabasic rocks to serpentinites and carbonate schists, and (2) the presence of metamorphic aureoles in the sediments enclosing the ultrabasic rocks. Both (1) and (2) were presumably effected by granitic rocks exposed nearby.

Several descriptions of magnetite veining chromite have appeared in the European literature, particularly by Horninger (3), and Ramdohr (6, p. 724). Photographs accompanying the accounts of Horninger and Ramdohr, however, show a slightly different texture from the one in Figures 2a and 2b of the present paper. Their chromites contain an intermediate-compositioned mineral, visible only with high power magnification or oil immersion,



FIGS. 2a and 2b. Two photomicrographs of magnetite veinlets in chromite. Magnetite (light gray), chromite (dark gray), serpentine (black). Small black spots in chromite are surface pits. Chrome Hill, Newfoundland. (× 60, plain light.)

lying zonally between the chromite cores and the magnetite veins. The magnetite and the intermediate-compositioned phase, called "gray magnetite" by Horninger although interpreted as an iron-enriched chromite, occur around the borders of, and along fissures in, the chromite grains. The "gray magnetite" is believed to have formed through the outward migration of iron from the centers of the chromite grains during the metamorphism of the enclosing rocks.

It is possible that the three component mineral texture described and illustrated by Horninger and Ramdohr is merely a more advanced form of the two component texture illustrated in the present paper. However, it seems more probable that the two textures are basically different, perhaps because of different environmental factors at the time of origin. Just how these factors differed might be worth further investigation.

The abnormal magnetic property of chromites of the type discussed in this paper might indeed serve as an aid to chromite prospecting, as Snelgrove suggested, but in a negative way, for the presence of magnetite scattered minutely through the chromite could well render it unsuitable for commercial utilization.

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THE NATURE OF ARIZONITE

M. D. KARKHANAVALA

ABSTRACT

The evidence for discrediting the mineral is analyzed to show that the natural mineral cannot be regarded as a mere mixture of hematite, anatase, rutile and possibly ilmenite. Also it cannot be regarded as simply weathered ilmenite, though it may possibly be an alteration product of ilmenite formed under hydrothermal or metasomatic conditions. It is concluded that the mineral arizonite represents a specific and unique, though somewhat rare and unstable chemical compound. This is also supported from the author's separate work in the system Fe_2O_3-TiO_2.

INTRODUCTION

In 1909, Palmer (12) reported the discovery of a new mineral—arizonite, the chemical analysis of which closely corresponded to ferric metatitanate—$Fe_2(TiO_3)_3$ or $Fe_2O_3 \cdot 3TiO_2$. From measurements of the interfacial angles on a large imperfect crystal he concluded that the symmetry was monoclinic and not corresponding to any mineral then known. Nevertheless, the possibility of an alternate symmetry was not ruled out.

From the average chemical composition, Miller (9) and later Gillson (3) have presumed that arizonite, rather than ilmenite, is the essential constituent of the titanium bearing sands of several localities including that of Quilon, India. No X-ray evidence has ever been adduced in support of such a hypothesis. On the contrary, considerable doubt has been expressed about the existence of arizonite as a distinct and specific mineral and it has therefore been regarded (2, 8, 11, 13) as a discredited mineral.

In this paper the evidence for discrediting the mineral is analyzed and discussed, together with the pertinent results obtained by Karkhanavala and Momin (5) in a study of the system Fe_2O_3-TiO_2.

THE EVIDENCE FOR DISCREDITING ARIZONITE

The reasons advanced for discrediting arizonite are that (a) all recent attempts to synthesize it have failed and (b) its X-ray pattern could be interpreted as that of a mixture of hematite, anatase, rutile and possibly ilmenite.

Gmelin (4) has reported the only successful synthesis of $Fe_2(TiO_3)_3$ by Muthmann and coworkers in 1907. It is reported to form by high temperature reaction of an appropriate mixture of the component oxides, but no physical or chemical property is described. Pesce (13) in 1931 failed in an attempt to synthesise ferric metatitanate by reacting appropriate mixtures of Fe_2O_3 and TiO_2 at 1,000° C in presence of NaCl as a flux. His work was confirmed by Overholt, Vaux and Rodda (11) in 1950. Ernst (2)

in 1943 obtained only a mixture of pseudobrookite and rutile when he fused 1 mole Fe_2O_3 and 3 moles TiO_2 at about 1,500° C.

The reported X-ray powder-photograph pattern of the original mineral (U. S. National Museum Collection No. 86, 973) was interpreted by Overholt, Vaux and Rodda (11) as due to a mixture of hematite, ilmenite, anatase and rutile. They therefore concluded that arizonite was simply weathered ilmenite. A similar conclusion was drawn in 1954 by Lynd and coworkers (8) from the X-ray pattern of a sample of arizonite from Hockberry, U.S.A., which according to them could be resolved as due to 40 percent hematite, 40 percent anatase and 20 percent finely crystalline rutile. They have also cited Ernst (2) who had previously shown that considering the accuracy of Palmer's original measurements of the interfacial angles with a contact goniometer, the values could, with equal justification be interpreted as due to rhombohedral symmetry corresponding to hematite.

Fresh Attempts at Synthesis.—In the course of a wider study (5) of the subsolidus reactions in the system Fe_2O_3-TiO_2, special attempts were made to synthesis the compound ferric metatitanate. All the previous attempts were made at atmospheric pressure under dry conditions but none under hydrothermal conditions, and numerous minerals are known which can be and have been synthesized only under hydrothermal conditions. The presence of water vapor under high pressures is a major factor in the successful synthesis of such compounds (10). Mixtures of the coprecipitated hydroxides corresponding to and in the vicinity of the composition $Fe_2O_3 \cdot 3TiO_2$ were therefore reacted under dry and hydrothermal conditions.

The reaction of these hydroxides in air, in the temperature range 600–1,200° C, for periods of 3 to 48 hours, yielded only mixtures of pseudobrookite and rutile, as previously obtained by Ernst (2). However, their reaction under hydrothermal conditions at 300° C and 1,200 p.s.i. for 10 days yielded promising results. Even though equilibrium was not attained, and some quantities of hematite and anatase were left over, yet sufficient evidence was obtained to indicate the formation of a small quantity of arizonite. The X-ray evidence on which this conclusion was based, is discussed together with the other X-ray data.

Critical Appraisement of the X-ray Evidence.—The standard powder pattern of arizonite (11) (A.S.T.M. card No. 6-0227) together with the standard patterns of anatase, hematite, rutile, ilmenite, and the observed pattern of the $Fe_2O_3 \cdot 3TiO_2$ hydrothermal product are listed in Table 1.

An objective analysis of the arizonite pattern, even assuming that it is a mixture of different compounds, shows that there is no need to postulate the existence of ilmenite in the mixture. Almost all the d-values (ignoring the intensities) can be accounted for by those of hematite, anatase and rutile, within ± 0.01 A, the normal accuracy obtainable photographically except for one line where the divergence is −0.02 A.

The principal d-spacings of ilmenite 2.74^{100},[1] 1.72^{100} and 2.54^{85} A, are different by + 0.08, + 0.033 and + 0.03 A, respectively, from the nearest lines of arizonite. The only reason for postulating the existence of ilmenite

[1] Superscripts refer to the intensities of the particular line.

TABLE 1

COMPARISON OF THE D-VALUES OF ARIZONITE, HEMATITE, ANATASE, RUTILE, ILMENITE AND THE $Fe_2O_3 \cdot 3TiO_2$ HYDROTHERMAL PRODUCTS

$Fe_2O_3 \cdot 3TiO_2$				Arizonite A.S.T.M. 6-0227		Hematite A.S.T.M. 6-0502		Anatase A.S.T.M. 4-0477		Rutile A.S.T.M. 4-0563		Ilmenite A.S.T.M. 3-0799	
G.M. counter CuKα		Photographic FeKα											
d	I/I_0	d	I/I_0	d	I/I_0	d	I/I_0	d	I/I_0	d	I/I_0	d	I/I_0
3.67	45	3.67	25	3.67	40	3.67	70					3.73	50
3.50	50	3.48	40	3.50	100			3.51	100				
3.23	45	3.22	60	3.23	30					3.245	100		
2.69	100	2.68	75			2.689	100					2.74	100
2.667	45			2.66	90								
2.51	70	2.51	60	2.51	80	2.508	80					2.54	85
2.49	35	2.47	25	2.48	0					2.489	41		
2.47	35							2.435	9				
2.37	22	2.37	10	2.37	10			2.379	22	2.297	7		
2.20	32	2.19	40	2.20	20	2.198	70			2.188	22	2.23	70
				2.18	0								
				2.08	0			2.054	9				
1.89	20	1.88	22	1.885	10			1.891	33				
				1.863	0							1.86	85
1.837	40	1.843	40	1.833	20	1.833	70						
1.689	90	1.683	100	1.687	70	1.688	80	1.699	21	1.687	50	1.72	100
1.667	35	1.659	5	1.660	30			1.665	19				
1.628	15	1.626	5	1.624	5	1.631	10			1.624	16	1.63	50
1.600	15					1.593	40						
								1.494	4			1.50	85
		1.477	40	1.478	30	1.481	70	1.480	13	1.480	8	1.47	85
		1.358	10	1.359	10			1.367	5	1.360	16		
		1.339	10	1.334	10	1.345	20	1.337	5	1.347	7	1.37	70
		1.304	5	1.308	0	1.306	40			1.305	1		
		1.284	10									1.27	60
		1.261	15	1.261	20			1.264	10				
						1.253	30	1.250	3				
		1.248	10							1.243	3		

seems to be the belief that arizonite is weathered ilmenite and hence the hope that some unaltered ilmenite might be left over. In this connection it is essential to note the conclusions of Axelrod (who had taken the original photograph) as quoted by Overholt et al. (11): "arizonite is a mixture,

TABLE 2

COMPARISON OF THE CORRESPONDING LINES OF RUTILE AND ARIZONITE

Rutile A.S.T.M.			Arizonite A.S.T.M.	
d	I/I_0	I/I_0	d	I/I_0
	$d_{1.245} = 100$	$d_{1.245} = 30$		$d_{1.51} = 100$
2.489 (3rd strongest)	41	12.3	2.48	0.0
2.297	7	0.21	—	—
2.188 (4th strongest)	22	6.6	2.19	0.0

principally of anatase, with hematite doubtfully present (spacings correct, but intensities not checking), and a fine-grained phase present whose pattern is very similar to that of ilmenite but with spacings different from those of the natural ilmenites which he has studied."

The absence of any reference to rutile in the above conclusions of Axelrod is very significant, as the assumption for the existence of rutile is based on the very doubtful equivalence of only one line at 3.23 Å, relative intensity 30 in the arizonite pattern. Assuming that this line is the 100 intensity line of rutile at 3.245 A, then the other lines of rutile that have similarly no overlap from either the hematite or the anatase lines, should also be present with only proportionate reduction in their intensities. On comparison (Table 2) of only such lines with the corresponding lines, if any, in the arizonite pattern, it is found that the assumption is not justified as there is complete disagreement in the intensities.

TABLE 3

RELATIVE INTENSITIES OF SOME ARIZONITE LINES WITH RESPECT TO HEMATITE 2.69 AS 100 (5)

Composition	Line at 2.66 A	Line at 3.23 A
$4Fe_2O_3 \cdot TiO_2$	8	10
$3Fe_2O_3 \cdot TiO_2$	18	N.D.*
$2Fe_2O_3 \cdot TiO_2$	33	35
$Fe_2O_3 \cdot TiO_2$	39	40

* Not determined.

While the existence of rutile is not justifiable for the natural sample, it is impossible in the case of the synthetic samples studied (5). Under the experimental conditions of 300° and 1,200 p.s.i. anatase is the stable phase and was the only phase to form. A blank sample of pure titanium hydroxide was found to crystallize into anatase only. Also Osborn (10) has shown that under hydrothermal conditions the lowest temperature at which anatase would convert to rutile is about 550° C provided the pressure applied is about 35,000 p.s.i. or more. As the pressure is lowered, the transformation temperature increases and approaches the limit (about 950° C) at atmospheric pressures. It must therefore be concluded that even though the 3.23 A line is observed in the synthetic samples, rutile is not and cannot be present in them and its presence should not also be assumed in the natural sample.

The presence of hematite though obviously more plausible, is actually doubtful. As Axelrod (11) has pointed out earlier, the spacings are almost correct but intensities do not check. The existence of hematite becomes still more doubtful, if the slight differences in the d-spacings are considered as genuine and not attributed to experimental errors. In the case of ordinary powder photographs, it is admittedly difficult to assign unambiguously between lines at 2.66 and 2.69 Å, and it is reasonable to consider that they represent probably the one and the same line. Also in case both exist, the more intense line will mask the other, as was actually observed in the powder photograph of the hydrothermal synthetic product.

However when these products were examined on the diffractometer under conditions of maximum resolution and using filtered CrK_α radiation unmistakable evidence was obtained (5) for the uniqueness of the arizonite line at 2.667 Å ($CrK_{\alpha_1} 2\theta = 50.85$) as distinct from the 2.691 Å ($CrK_{\alpha_1} 2\theta = 50.37$) line of hematite. The fact, that increasing amounts of arizonite were formed as the compositions approach $Fe_2O_3 \cdot 3T_1O_2$ is obvious from Table 3 (reproduced from (5)) wherein the ratios of the relative intensities of the 2.66 A and the 3.23 A line of arizonite with respect to the 2.69 Å hematite line as 100 are tabulated.

From the increasing peak height ratios of the arizonite to hematite lines, it was clear that the amount of free Fe_2O_3 decreased and that of arizonite increased as the arizonite composition was approached. Because of the secondary fluorescent X-rays from Ti with CrK_α radiation, it was not possible to examine with this radiation composition richer in titanium than $Fe_2O_3 \cdot TiO_2$ (33.3 percent TiO_2).

TABLE 4

COMPARISON OF COMMON LINES OF ARIZONITE AND ANATASE

Arizonite		Anatase	
d	I/I_0	d	I/I_0
3.50	100	3.51	100
2.37	10	2.379	22
1.885	10	1.891	33
1.660	30	1.665	19
1.261	20	1.264	10

One must therefore conclude, as Richmond of the U. S. Geological Survey has done in his report to Overholt et al. (11): "There are sufficient differences in the spacings and arrangements of the diffractive lines to preclude its identity with hematite. The powder photographs of hematite, arizonite and ilmenite are similar but the spacings of the same diffracting planes of each mineral is different. This probably means that all three minerals have the same structure cell but the cell edge lengths vary slightly with composition."

Regarding the presence of anatase, no definite conclusions can be drawn from the study of the artificial hydrothermal products. Tentative but inconclusive evidence for the probable existence of both the anatase line at 3.513 Å ($CrK_{\alpha_1} 2\theta = 38.04$) and the arizonite line at 3.504 Å ($CrK_{\alpha_1} 2\theta = 38.12$) were obtained. However since equilibrium was not attained even after 10 days, the presence of free anatase was to be expected. From a close scrutiny (Table 4) of the relative intensities of the anatase-like lines in the arizonite pattern, it is my opinion that the near identity of the d-spacings should be treated as mere coincidence, since the intensities do not check, and that these lines should not be considered as evidence for the existence of anatase in natural arizonite.

There is therefore no real justification for regarding the X-ray pattern of natural arizonite as composed of a mixture of hematite, anatase, rutile and ilmenite. Also the fact that it cannot be synthesized under dry conditions at atmospheric pressure is not an adequate reason to deny its existence in

nature. The limited success obtained (5) in synthesizing arizonite under hydrothermal conditions is considered enough justification to accept its occurrence in nature, may be as a rare mineral, with possible rhombohedral symmetry similar to hematite or ilmenite.

It is quite possible that the mineral has a very limited stability, since the hydrothermal products obtained in the study of the system Fe_2O_3-TiO_2 tended to decompose and resemble the products of the dry runs (psendobrookite and rutile) on subsequent heating in air at temperatures above 400° C.

In the synthetic sample because equilibrium was not attained, the product was not a single compound, but a mixture of hematite, anatase and arizonite. Hence in the X-ray pattern the absolute values of relative intensities of the arizonite lines could not be determined due to the presence of strong lines of hematite, and anatase in the close vicinity. There are therefore a few obvious discrepancies between the reported and observed relative intensity values of the natural and synthetic mineral. Some of these differences may however be genuine.

IS ARIZONITE WEATHERED ILMENITE?

Overholt and associates (11) have regarded arizonite as "merely weathered ilmenite." The term "weathering" is often loosely applied to cover many alteration processes, but is generally applied to alterations due to atmospheric oxidation or hydration only. It is rarely applied to any type of metasomatic alterations. If this definition of the term "weathering" is accepted, then arizonite cannot be regarded as weathered ilmenite.

The conclusion of Overholt et al. (11) is surprising because they have themselves experimentally confirmed the earlier observations of Ramdohr (14) that oxidation of ilmenite in air leads to the formation of pseudobrookite and rutile. Karkhanavala and Momin (6) have also obtained similar results, except that small amounts of hematite were also found to be present in addition to pseudobrookite and rutile. These hematite lines are barely visible in an ordinary powder photograph, and probably, therefore hematite was not reported previously (11, 14).

Overholt et al. (11) have claimed that the physical properties of arizonite were duplicated by the oxidation product of ilmenite heated overnight at 900° C. May be some physical properties like color are similar to the two, but the X-ray pattern of ilmenite heated at 900° C. which is essentially that of a mixture of pseudobrookite and rutile together with small amounts of hematite, is markedly different from that of arizonite (Table 1). So whatever may be the similarity in the physical properties, the chemical composition of the oxidation product and arizonite are certainly different.

Arizonite may be an alteration product of ilmenite, but it is not the product of atmospheric oxidation. This conclusion is supported by the work of (a) Bailey, Cameron, Spedden and Weege (1) who in their study of the alteration ilmenite taking place naturally in the beach sands, did not find any evidence for the presence of arizonite. (b) Karkhanavala et al. (6, 7) in their study of the titanium-bearing sands of Quilon, India, which

are supposed (3, 9) to contain arizonite, found no X-ray evidence for its presence. The commercial ilmenite concentrate from these sands yielded an X-ray pattern of ilmenite, and the alteration products—the commercial leucoxene concentrate—yielding X-ray patterns of mixtures of pseudobrookite, hematite, anatase and rutile in different proportions.

It is surmised therefore that arizonite probably forms by the hydrothermal alteration of ilmenite. The fact that it can be synthesized only under hydrothermal conditions, suggests a hydrothermal origin in nature also.

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Oct. 21, 1958

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SCIENTIFIC COMMUNICATIONS

MONAZITE-BEARING PEGMATITES IN THE SOUTH GEORGIA PIEDMONT

CHARLES W. FORTSON, JR. AND ALFRED T. NAVARRE

On three occasions during the last four years, the writers visited an area in the South Georgia Piedmont to examine monazite-bearing pegmatites. The area is near the intersection of Crawford, Monroe, and Upson counties, just south of Culloden, Georgia.

A few pegmatite occurrences are known in the Monazite Belt. Another site has been reported from the Georgia Piedmont, some 10 miles northwest of the area covered in this discussion (5), but the writers did not see it. Other scattered occurrences probably exist in this part of the state and more work should be done to determine their sites and relations.

Geologically, the area lies on the southern side of the Wacoochee Belt, as defined by Crickmay and others (2, 3, 4) and is bounded on the north by the Towaliga Fault and on the south by the Goat Rock Fault, both of which trend northeast–southwest. The pegmatites occur in shear zones at two sites in what is thought to be part of the Goat Rock Fault zone. The pegmatites themselves occur on two low hills less than one mile apart on property leased by Dr. Carsbie Adams of Atlanta. The area studied is somewhat south of the extensively-mined Thomaston-Barnesville mica district (4) and geologic relations are obscure. There are undoubtedly undiscovered pegmatites as evidenced by widely separated, but extensive, radiometric highs and small scattered exposures obscured by weathering.

PETROGRAPHY AND STRUCTURE

The area is underlain by metamorphic rocks, some of which are highly sheared. It is thought that the cataclastic zones represent an eastward continuation of the Goat Rock fault. The unit labeled Schist-Gneiss-Amphibolite (Fig. 1) is a complex series of what in many places appears to be metamorphosed volcanic rocks, perhaps similar to those of the Carolina Slate Belt and the Little River Series, only a higher metamorphic grade. Rhyolite and breccia occur just southwest of the area. Many of the hornblende gneisses and phyllites commonly contain angular fragments, some of which are thought to be pyroclastic in origin.

At point 1 (Fig. 1), the pegmatite is an elongated and semiconcordant body that filled openings or potential openings in portions of sheared biotite gneiss. Its dimensions are unknown due to poor exposures. Samples taken

from two prospect holes were quartz-potash feldspar pegmatites with occasional small crystals of monazite less than ¼ inch in largest dimension. Local segregations of a pitchy black biotite, assimilated from the county rock, do not readily weather as does ordinary biotite. The trend of the pegmatite is approximately N 40° E.

At point 2 (Fig. 1), two types of occurrences were seen. The first occurs as scattered semiconcordant veinlets of pegmatite similar to that already described. In 1955, one of the writers (Navarre) observed another type of

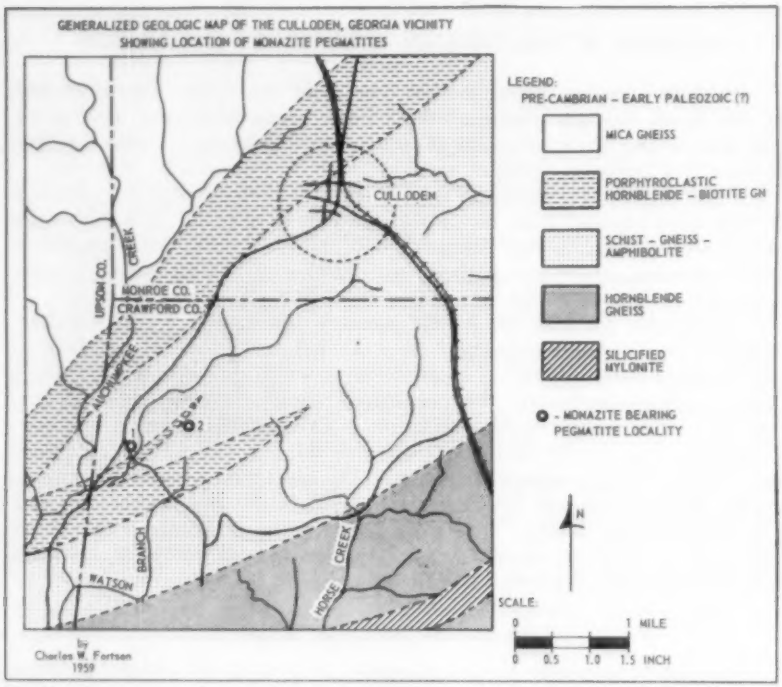

FIG. 1.

occurrence in a weathered bank in which larger crystals of monazite definitely cut across the foliation and had no other mineral associates. Several dozen samples were taken by Navarre, Dr. Adams, and an Anaconda Copper Mining Company geologist at that time. The site has subsequently been excavated and could not be examined on recent trips. Most of the pegmatites at this site are small, being commonly only a few inches in thickness. The quantity of monazite is generally less than 2 percent by volume, according to Dr. Adams (1). Other minerals occurring in the first type in small quantity at site No. 2 are graphite, ilmenite, and zircon.

GENETIC RELATIONS

The origin of the pegmatites is speculative. They were probably injected after the major shear zones were developed, during or after Permian time. A definite age for the rocks in the area has not, however, been proposed. Small quantities of monazite occur in some garnet-pyroxene and garnet-biotite granites a few miles west of the area. Blue quartz, common in these granites, also occurs in some of the local pegmatites. It is possible that the pegmatites were derivatives of these granites. The Wacoochee Belt itself perhaps was uplifted in part by the forces of intrusion, followed by pegmatitic intrusions filling fractures and shear zones.

ENGINEERING EXPERIMENT STATION,
GEORGIA INSTITUTE OF TECHNOLOGY,
July 28, 1959

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VERTICAL FAULT DISPLACEMENTS OBTAINED FROM AIRPHOTOS

D. H. ELLIOTT

The approximate vertical displacement of faults can be obtained in many cases from a stereoscopic study of vertical airphotos, using only one simple measurement which involves no parallax measurements. Two methods are used—the first for faults that offset beds having appreciable dip, and the second for faults that displace flatlying beds. In both cases, it is necessary to identify a specific bed on both sides of the fault.

The procedure for each method is as follows:

First Method—for Beds Having Appreciable Dip

1. Under the stereoscope, draw the fault trace with a fine line (a Rapidograph #0 pen filled with black india ink is satisfactory).

2. While examining the fault area in three dimensions under the stereoscope, extend a fine line along strike to the fault from a high point on the offset bed, keeping the line at the same apparent elevation on the stereo model. (This line will be at the same elevation automatically if the line is extended in the direction of strike.) This means that the line of extension of the high point will meet the fault at a different point than the actual trace of the bed.

3. On the opposite side of the fault, extend a line along strike to the fault from a point at the *same* elevation as on the first side of the fault.

4. Measure (non-stereoscopically) in *decimals of a foot* this offset distance on the airphoto between the two extended points at the fault trace. This

measurement can be made best with a tube magnifier, which can be read directly to .001 foot. In those cases where the fault trace does not trend at right angles to the strike, the measurement should be made next to the fault at right angles to the strike.

5. This measurement should be multiplied by the scale factor of the airphoto: i.e., 20,000 in the case of a 1:20,000 scale. The resultant figure represents the ground horizontal displacement of the fault in feet.

6. Estimate [1] the dip of the bed at the fault.

7. Using trigonometry, the true vertical displacement of the fault can be found using the following equation:

$$\tan \text{angle dip} = \frac{\text{vertical displacement (in feet)}}{\text{horizontal displacement (in feet)}}$$

Second Method—for Flatlying Beds

1. Under the stereoscope, mark the fault trace as in the first method.

2. Mark on the airphoto close to both the fault and the offset bed, several tiny dots spaced at .005 foot. The ground distance represented between each of the dots will be equal to the photo scale factor multiplied by .005 feet. In the case of 1:20,000 airphotos, the distance will be 100 feet.

3. Under the stereoscope, using the ground distance between each dot as a base, estimate in feet the *apparent* vertical displacement of the bed at the fault.

4. The true vertical displacement of the fault in feet can now be obtained by dividing the apparent vertical displacement (found in Step #3) by the vertical exaggeration factor of the stereo model. In the case of standard 1:20,000 airphotos taken with an 8¼-inch lens and having an overlap of 60 percent, the exaggeration factor approximates 3 (using a CF-8 lens stereoscope).

This method may also be used for estimating the height of cliffs or hills, in addition to the fault displacement outlined above.

The results of those calculations-estimations are only approximations. However, for a competent interpreter, a plus-or-minus 10 percent accuracy for the first method (within a medium range of dips), and a plus-or-minus 20 percent for the second method can be expected. The possible sources of inaccuracies—the varying photo scale, the estimate of dip, the vertical exaggeration factor, etc.—are obvious. Nevertheless, in spite of these, the two methods described provide a quick and easy way to ascertain the approximate vertical displacement on faults on the airphotos.

CASPER, WYOMING,
July 28, 1959

[1] A quick method for estimating the angle of dip is outlined as follows, for 1:20,000 airphotos, 8¼-inch lens, and 60 percent overlap:

1. Estimate the *apparent* dip under the stereoscope.
2. Find the tangent of the apparent dip.
3. Divide the tangent by 3 (which is the average exaggeration factor in airphotos having the specifications mentioned above).
4. Determine the true angle of dip from the tangent found in Step #3.

VADEMECUM TO THE RUSSIAN GEOLOGICAL PERIODICALS

EUGENE A. ALEXANDROV

Name of the periodical	*Subjects covered*
1. AKADEMIYA NAUK SSSR, IZVESTIYA, SERIYA GEOLOGICHESKAYA (Academy of Sciences of the USSR, News, Geological Series). Published since 1935. 12 issues per annum. Each issue contains about 130 p., and 7 to 12 articles.	Stratigraphy, tectonics, lithology, petrography, mineralogy, geochemistry, mineral deposits, and history of geology. Contents in English.
2. AKADEMIYA NAUK SSSR, DOKLADY (Academy of Sciences of the USSR, Reports). 27th year of publication. 36 issues per annum. Each issue contains 150 p., and 10 to 12 articles dedicated to earth sciences.	The journal includes short articles (not over 4 pages) on geology, ground water hydrology, mineralogy, crystallography, petrography, geochemistry, soil science, and paleontology. Papers are accepted for publication in this journal only if recommended by an academician. Contents in English.
3. VSESOYUZNOE MINERALOGICHESKOE OBSHCHESTVO, ZAPISKI (Journal of the Allunion Mineralogical Society). Published since 1866. 6 issues per annum. Each issue contains 130 to 150 p., and about 15 articles.	Research in mineralogy, crystallography, petrography, theory of genesis of minerals, geochemistry, new minerals and rocks, and experimental studies. Contents in English.
4. SOVETSKAYA GEOLOGIYA (The Soviet Geology). Published by the Department of Geology and Conservation of Mineral Resources. 12 issues per annum, 130 to 150 p. in each, and about 10 articles.	General geology, stratigraphy and paleontology, petrography, mineralogy, tectonics, geophysics, ground water hydrology, economic geology, exploration of mineral deposits, and methods of geological survey. English summaries. Contents in Chinese.
5. GEOKHIMIYA (Geochemistry). Published by the Academy of Sciences of Soviet Union. 8 issues per annum, 80 to 100 p. and 12 papers in each.	Experimental and theoretical geochemistry, mineralogy, crystal chemistry, chemistry of the universe, and other subjects related to geochemistry, such as distribution of elements and their isotopes, thermodynamics, physical chemistry and chemistry of natural processes, and methods of geochemical exploration. English abstracts.
6. KRISTALLOGRAFIYA (Crystallography). Published by the Academy of Sciences of the USSR. 6 issues per annum, about 120 p. and 12 papers in each issue.	X-ray study of crystals of chemical compounds, alloys and minerals; electronic density of crystals; optical and physical properties of crystals; growth of crystals; application of infrared rays to study of minerals; instruments; educational problems.
7. RAZVEDKA I OKHRANA NEDR (Exploration and Conservation of Mineral Resources). Published by the Department of Geology and Conservation of Mineral Resources. 12 issues per annum, 60 p. and 7 to 12 articles in each issue.	Geological prospecting, exploration, study of ground water, geophysical prospecting, geology of particular deposits and regions (including petrolcum deposits), and methods of complex study of a mineral deposit. Achievements of geological exploratory teams and equipment used in the field.
8. AKADEMIYA NAUK SSSR, IZVESTIYA, SERIYA GEOFIZICHESKAYA (Academy of Sciences of USSR, News, Geophysical Series). 12 issues per annum, about 115 p. and 10 articles in each.	Theoretical, applied, and exploratory geophysics; geophysical instruments; physics of the sea; meteorology.

Name of the periodical	*Subjects covered*
9. GEOLOGIYA NEFTI I GAZA (Geology of Petroleum and Gas). Published by the State Scientific and Technical Committee of the Council of Ministers of the USSR. 12 issues per annum, 75 pages and 10 to 12 articles in each.	Petroleum geology, sedimentation, origin of hydrocarbons, petroleum prospecting, and application of geophysical methods to petroleum exploration. English contents.
10. POCHVOVEDENIE (Soil Science). Published since 1899. About 112 p. and 10 articles in each issue.	Geographical distribution of soils, physicochemical processes in soils, activity of bacteria in soils, trace elements, and dynamics of soil humidity. English abstracts.
11. IZVESTIYA VYSSHIKH UCHEBNYKH ZAVEDENII, GEOLOGIYA I RAZVEDKA (News of the Institutions of Higher Learning, Geology and Exploration). Published since 1958. 12 issues per annum, 125 p. and 12 to 16 articles in each.	Geology, mineralogy, petrography, mineral resources, methods and technique of exploration, ground water hydrology and engineering geology, geophysical methods of prospecting, and defense of dissertations.
12. VESTNIK MOSKOVSKOGO UNIVERSITETA (Herald of the Moscow University), Biological, Geological, and Geographical Series. Published since 1945. 4 issues per annum, 60 p., and 8 to 9 articles (geology) in each.	Regional tectonics, geomorphology, soil science, petrography, mineralogy, economic geology, stratigraphy, and paleontology.
13. VESTNIK LENINGRADSKOGO UNIVERSITETA (Herald of the Leningrad University). Geological and Geographical Series. Published since 1945. Quarterly, 55–85 p. and 4 to 10 geological articles in each issue.	Stratigraphy, tectonics, structural geology, mineralogy and crystallography, surveying instruments, paleontology and micropaleontology, ground water, equipment for mineralogical laboratories, geochemistry, economic geology, geomorphology, geophysics. English summaries.
14. AKADEMIYA NAUK SSSR, REFERATIVNYI ZHURNAL, GEOLOGIYA (Academy of Sciences, Geological Abstracts). 12 issues per annum, about 300 p. in each issue.	Covers all earth sciences. During 1958, 22,202 articles and books have been abstracted. The interval between the publication of the original material and the publication of the abstract is about 10 months. About 25 percent of all material is Russian.

Besides these publications, during 1958, in the Soviet Union have been published some 112 geological journals, transactions, and bulletins. Together with the 14 journals reviewed, it makes 126 publications. Out of this number, 12 are published by the Academy of Sciences, 8 by the laboratories of the Academy of Sciences, 10 by the regional branches of the Academy, 18 by the academies of sciences of the republics of the USSR, 12 by the research institutes, 12 by the schools of mines and engineering schools, 15 by the universities, 8 by the teachers' colleges, 3 by the museums, and 28 by the geological survey and other institutions.

A part of these periodicals is abstracted in United States by the Geoscience Abstracts and by the Engineering Index. The Geochemical Society is translating "Geokhimiya." Attempts are being made to translate two or three other journals.

DEPARTMENT OF GEOLOGY,
COLUMBIA UNIVERSITY,
June 24, 1959

Economic Geology
Vol. 54, 1959, pp. 1315–1323

DISCUSSIONS

THE DECOMPOSITION OF ILMENITE

Sir: The origin of leucoxene has often been discussed and usually is ascribed to the weathering of ilmenite and sphene. Especially leucoxene in association with ilmenite sands is most likely a weathering product. This material may give an X-ray pattern of rutile or anatase, but rarely brookite (2). V. C. Allen (1) believes that some leucoxene is amorphous. The present writer agrees with him in the sense that the material is of particle sizes and quantities that the X-ray diffractometer cannot record. This is, of course, not a unique property of leucoxene.

Weathering is not the only process that makes ilmenite into TiO_2 and accompanying iron oxides and hydroxides. A very efficient way of breaking down ilmenite is to expose it to H_2S at elevated temperatures. The reactions

$$FeTiO_3 + H_2S \rightarrow TiO_2 + FeS + H_2O$$

$$FeS + H_2S \rightarrow FeS_2 + H_2$$

are probably well known to geologists but the writer knows of no experiments that would indicate the temperatures at which these changes occur. Our experiments show that ilmenite alters to rutile and pyrite at 300° C in a dry stream of H_2S. A finely ground ilmenite of relatively high purity from Grayson County, Virginia, was used. When larger pieces of this material or those from Arendal, Norway (which contained some magnetite) were used they decrepitated and could not be polished afterwards.

The reactions on powder were incomplete in 210 hours but X-rays showed rutile and pyrite distinctly. The pyrite could be removed with nitric acid. At higher temperatures up to 600° C the action was much more rapid. It may be safely assumed that even temperatures lower than 300° C could be quite effective given sufficient time.

When ilmenite was heated in a closed system of water saturated with H_2S (at room temperature) and at saturated vapor pressures at 220° C alteration also occurred. These experiments must be made in sealed glass containers inserted in steel autoclaves. As the glass is attacked under these conditions the runs cannot be continued indefinitely. Two of four experiments showed the following results: Temperature 220° C, time 960 hours. Considerable pyrite had formed but no rutile could be detected. Perhaps it is reasonable to assume that, since pyrite could not have formed without freeing of TiO_2, the latter is present in such size that X-rays are not diffracted, in other words, in the form of amorphous leucoxene. In the second experiment at temperature of 200° C, time 192 hours, no significant change was detected.

It is probable that these experiments may point up a number of field occurrences. One that comes to the writer's mind is Ramdohr's "Pronto Reaktion." Ramdohr observed this reaction, for which no chemical equation can be written, in uranium ore of the Pronto Mine of the Blind River District, Ontario. Here ilmenite has evidently been decomposed to rutile or anatase and the TiO_2 in turn has reacted with UO_2 to form brannerite, a complex U-Ti-Fe oxide. Pyrite, pyrrhotite, and uraninite are associated. The iron sulfide is always extremely abundant and suggest the action of H_2S. The geologic setting indicates elevated temperatures. Two experiments with uranyl sulfate sodium titanate and H_2O saturated with H_2S were run at 220° C for 400 hours. The results were good uraninite and anatase. Evidently the complex brannerite forms only at higher temperatures and pressures.

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DEPARTMENT OF GEOLOGY,
UNIVERSITY OF MINNESOTA,
June 24, 1959

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FURTHER OBSERVATIONS ON URANIFEROUS CONGLOMERATES

Sir: In several publications I have directed attention to two fundamental geochemical criteria whereby the banket ores of the Witwatersrand, Blind River and elsewhere can be distinguished from radioactive mineralization of unquestioned detrital origin. First, in the Witwatersrand-type formations the highest uranium content is almost always associated with the country-rock sediments of coarsest grain size, this being the antithesis of the distribution pattern habitually found in the radioactivity logging of younger strata. Second, in the banket ores uranium is consistently in excess of thorium, in this contrasting with alluvial ores where thorium is invariably in excess of uranium. The validity of these two distinctions has lately been challenged in some arguments which seem to merit analysis. Other aspects of the present controversy will be reviewed elsewhere.

On the first point, Ramdohr has claimed in two recent papers (1, 2) that the direct relationship of radioactivity to grain-size, giving the highest uranium contents in the conglomerates, is in itself a sufficient indication of the sedimentary origin of the uraninite, for a mineral of very high specific gravity must, in his view, preponderate in the coarsest detritus. This is a noteworthy example of subjective reasoning. The rounded uraninite particles are assumed by Ramdohr to be detrital, so he names them *"Gerölle,"* which in turn he translates as "pebbles" (3). Being "pebbles," they must accumulate in the conglomerate. He records no measurement of the size of these "pebbles";

but according to more than 25,000 determinations by Liebenberg (4), their average diameter in the Witwatersrand ore is 75 microns, with a range of from 10 to 200 microns. In fact, the particles are no more than silt-sized, and Ramdohr's terms *"Gerölle"* and "pebbles" are an indefensible misuse of language. Now, since the mean diameter of the quartz grains in the Witwatersrand quartzites is 1.4 mm (5), it can readily be calculated that in water the average uraninite particle is roughly a thousand times *lighter* in weight than the average quartz grain. Applying the Stokes formula, particulars of which can be found in most text-books on sedimentation, and assuming specific gravities of 2.6 for quartz and 9.0 for uraninite, it becomes apparent that the rate of settling in water of the average quartz grain in the Witwatersrand quartzites is 70 times speedier than that of the average uraninite particle in the bankets. Why, then, if the uraninite is detrital, should it preferentially accumulate in high concentration solely or principally within the conglomerates? That is does so, contrary to the elementary principles of sedimentation, is an eloquent demonstration that it cannot be alluvial.

Concerning this same issue Wiebols (6) categorically refutes my generalization concerning the Witwatersrand that: "In any single sedimentary cycle within the System, the radioactivity progressively decreases as one passes from conglomerates through quartzites and argillaceous quartzites to shales." He claims, on the basis of "numerous radio logs" which are not published, that the quartzites and shales are equally radioactive, with variations both ways. Is not this in itself a strange departure from the normal order of things, wherein the shales would be by far the more radioactive? In his pioneer gamma-logging studies on the Witwatersrand Simpson (7) has noted, regarding the precise strata to which Wiebols refers, that:

> "Concentrations of radioactive material are not observed [at this horizon] but variations in [radioactivity] normal are found, the normal falling off as the sediments become more argillaceous. This feature is of interest as in younger sediments the normal of argillaceous strata is usually higher than that of arenaceous material."

And elsewhere Simpson (8) writes:

> "The succession of sediments in the Upper Witwatersrand beds tend to follow a well-defined rhythmic pattern in which at certain points quartzites tend to become coarse in texture and develop further through transition stages of grits and scattered pebbles into conglomerates. The cycle then reverses itself. Radioactivity logging has shown that these cycles of sedimentation are often associated with well-defined cycles of uranium deposition which may open slowly, reach a maximum with full development of the conglomerates, and then slowly die away."

These parameters cannot be paralleled in radioactivity studies of post-Proterozoic strata, apart perhaps from exceptional circumstances where the radioactivity is due to accumulations of radon in the more permeable rocks. Although he is apparently unaware of it, Wiebols is obtaining from the Witwatersrand succession gamma logs which bear almost an inverse relationship to the logs that oil geologists have produced on a vast scale from later sediments. Seemingly he does not realize that were it not for this inversion of normality he would not be logging in the Transvaal at all.

The second criterion of distinction between banket ores and true placers is the uranium : thorium ratio. In the Witwatersrand conglomerates the uranium content exceeds the tenor of thorium by a factor of about 25 : 1, a relationship which made it possible for most of the early development of the uranium mines to be conducted on the basis of uncorrected radiometric assays. On the other hand, throughout an immense array of published and unpublished work on alluvial deposits of all geological ages, executed since 1945 by the British, American, and Commonwealth Geological Surveys in connexion with uranium explorations, there has not been reported a single representative sample of a siliceous sand or gravel deposit bearing uranium in excess of thorium. There is thus a firm foundation for the deduction that the high uranium : thorium ratio in the banket ores must be attributed to other than syngenetic mineralization.

The soundness of this deduction has now been impugned by Friedman (9), by Ramdohr (1, 2), and by Roscoe (10), all of whom indulge in the quite fallacious reasoning that if a high uranium : thorium ratio is a mark of epigenetic origin, the reverse relationship must necessarily derive from syngenetic deposition. Contemplation of almost any primary thorium deposit exposes this *non sequitur*. For Blind River, Ramdohr claims that the urania : thoria ratio ranges from 20 : 1 to 1 : 150, that the relatively high uranium tenors which I have quoted are illusory since they refer solely to commercially developed ore (!), and that the preponderance of thorium in the Huronian conglomerates as a whole is evidence of the alluvial nature of all the mineralization there. Friedman and Roscoe argue along similar lines. For the Witwatersrand, Ramdohr explains that the low thorium content arises from a failure of monazite to become concentrated because of the relatively low specific gravity and inferior hardness of this mineral.

It would be interesting to have some confirmation of Ramdohr's bald assertion on the range of urania : thoria ratios at Blind River—from 20 : 1 to 1 : 150, *"also um den Faktor 3000!"* The most recently published report shows in considerable detail that the characteristic urania : thoria range in these rocks is from 8 : 1 to 1 : 10 (11) though exceptional occurrences are still richer in thorium relative to uranium (10). But neither from Blind River nor anywhere else has any thorium mineral or any thorium-bearing rock ever been recorded with a urania : thoria ratio of as low as 1 : 150, and I doubt very much whether any such rock exists. This, however, is a minor point. The following remarks are more pertinent.

The existence of these thoriferous Huronian sediments was referred to in my 1957 paper (12) in some sentences which its critics have seemingly omitted to read :

"Both in North America and South Africa a thorium-rich mineralization, entirely devoid of uranium minerals and sulphides, is to be found in sediments of the same age as the bankets and situated at no great distance from the mining fields. Thus in the Huronian quartzites of Michigan there is to be found the most extensive mineralization of monazite (7.6% ThO_2, 0.20% U_3O_8) ever seen in an ancient sediment, the uranium : thorium ratio of 3 : 1 in the conglomerates of Blind River changing to 1 : 38 some 200 miles to the west. Similarly in the Mozaan

quartzites of Swaziland there are radioactive horizons with monazite, thorite and zircon, but bearing neither uraninite nor sulphides. Comparable zircon-monazite associations have been recorded as heavy residues close to and roughly contemporary with the Algonkian bankets of Brazil. These thorium-rich mineralizations may be of hydrothermal origin, co-genetic with and perhaps zonal around the uraninite-gold-pyrite trinity; but accompanied as they are by grains of hematite, magnetite and ilmenite they have every appearance of being normal detrital assemblages, the same as alluvials of present-day deposition."

Thus the question of the origin of the thorium-rich mineralization was left open because of lack of evidence. Further work is needed to demonstrate whether the thorium mineralization is detrital or whether, both in Ontario and in the Transvaal (Dominion Reef), it is a hypothermal phase zoned around the mesothermal uranium mineralization.

The salient point of these remarks, unobserved by Friedman, Ramdohr, and Roscoe, is that in the relatively uranium-rich developments of the banket the uraninite (with or without brannerite) is almost always accompanied by pyrite, the sulfide commonly forming from two to 20 percent of the rock; whereas in the relatively thorium-rich strata the monazite and thorite associations are largely sulfide-free. At Blind River, even where identifiable uranium minerals are absent, a higher-than-normal uranium : thorium ratio in monazite (possibly due to uranothorite inclusions) is said to be accompanied by the entry of disseminated pyrite (11). The most elementary consideration of this distribution pattern leads to conclusions so obvious that I have not hitherto thought it necessary to enumerate them. Consider the specific gravities and hardnesses of uraninite, pyrite and monazite:

	Uraninite	Pyrite	Monazite
Sp. gr.	7.5–9.5	4.9–5.2	5.0–5.2
H.	5½–6	6–6½	5–5½

Manifestly, if recourse is made to a placer hypothesis it becomes impossible to explain the consistent sympathetic association of the heavy uraninite with the much lighter pyrite, and the antipathetic relationship of pyrite to the equiponderant monazite. No mechanism of hydraulic separation can explain these associations. To resolve this difficulty maybe my Canadian colleagues will proceed to "hydrothermalize" the pyrite at Blind River, to the confusion of Ramdohr who now recognizes three different types of pyrite *Geröllе* there. But if the pyrite is hydrothermal, why not the uraninite also?

The further conclusion of Ramdohr that in the Witwatersrand bankets monazite was not concentrated along with the "detrital" pyrite and uraninite because of its "low specific gravity and inferior hardness" may also be reviewed with profit in the light of the text-book figures given above. It is common knowledge that monazite is a ubiquitous placer mineral, worked from beach and valley deposits all over the world (13); but on the other hand, because of weathering, pyrite is rare in placers and alluvial uraninite is almost non-existent. The claim that the low thorium content of the South African reefs is to be explained in terms of the physical properties of monazite (under a methane atmosphere!) thus demands not only an inversion of the principle of uniformity but also some very peculiar behaviour on the part of the force

of gravity. When science ceases to be synonymous with sense it becomes nonsense.

C. F. DAVIDSON

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SCOTLAND,
July 10, 1959

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THE OCCURRENCE OF URANIUM IN ANCIENT CONGLOMERATES

Sir: In vol. 53, pp. 887–888 and vol. 54, pp. 313–324, respectively, of this journal Professor Davidson and Dr. Bosazza discuss the origin of the gold in the Ghana bankets and also refer to the 1930 publication by Kitson and Felton (*2*) containing the results of the microscopical examination of 639 Ghana concentrates, mainly from stream gravels. From the listed frequency of the minerals recognized in these concentrates, Davidson infers that pyrite must be a rare alluvial mineral in Ghana, and Bosazza that special conditions, for example the development of a protective coating during weathering, may have existed for the preservation of epidote, amphibole and pyroxene in the gravels.

Having collected and microscopically examined some of the concentrates, I wish to point out that these inferences are not justified as the concentrates were in no way representative of the average Ghana concentrate and were selected for petrological investigation because many of them contained unusual minerals or other minerals that could not be precisely determined in the field.

Moreover, many of the concentrates came from the immediate vicinity of outcrops and most of them containing sulphides were separately examined.

Pyrite, including limonite pseudomorphs after pyrite, is actually much more common in the gravels than its listed frequency would indicate, and Kitson in a previous publication (1) stated that it was one of the minerals most frequently found in concentrates from gravels and sands. This fact, however, does not affect the validity of Davidson's argument that the gold in the Ghana bankets must have been deposited in an oxidizing environment.

Dr. Bosazza's statement that "it is not unusual in the high rainfall areas in Ghana to find depths of complete decomposition to as much as 200 feet vertically" is somewhat misleading. It is true that certain rocks, such as the Birrimian volcanics, dikes and graywackes, are in places weathered to depths of 200 feet, for example, on lateritized residuals of erosion surfaces, but it is exceptional for them to be completely decomposed to such a depth. Actually, outcrops of fresh rock are very common in stream beds and are frequently found on higher ground. Even where there are no outcrops, determinable bedrock is generally present at a depth of less than 10 feet below the alluvium in valleys and also in trenches, pits and adits in hilly country. Exposures in hundreds of shallow adits in the mining fields show that the geology and structures are generally as well preserved as they are in deeper workings in solid rock.

As most of the listed concentrates containing epidote, amphibole and pyroxene came from south-eastern Ghana, where the rainfall is below average and outcrops are plentiful, it seems unnecessary to postulate special conditions for the preservation of these minerals in the Recent gravels.

The auriferous conglomerates of the Tarkwa goldfield have been studied in detail by the Government Geological Survey, and the geology of the goldfield and of the individual mines has been described in Memoirs 1 and 6 (3, 5) and Bulletin 10 (4) of the Survey.

The Tarkwaian, in which the bankets occur, unconformably overlies the Birrimian, which is a geosynclinal sequence of vast thickness, consisting of a lower suite, mainly argillites, graywackes and tuffs, and an upper suite of volcanics and basic intrusives.

A period of orogenic movements intervened between the Birrimian and the Tarkwaian, during which the Birrimians were folded, granitized and metamorphosed, then uplifted and intruded by post-tectonic granites and porphyries which were followed by widespread lode-gold deposition.

With one exception (Bibiani), all the principal lode-gold deposits are situated in a belt 120 miles long on the western flank of the Tarkwaian from Prestea to Konongo, and occur in direct association with deep-seated zones of shearing and faulting along the contacts between strips of Upper Birrimian volcanics with less competent Lower Birrimian sediments. The orebodies consist of two contrasted types, free-milling quartz reefs and refractory sulfide replacements, and the mineralization throughout the belt is monotonously similar, viz. pyrite, arsenopyrite, and gold with a little pyrrhotite and chalcopyrite.

The Tarkwaian sediments were mainly derived from the denudation of

Birrimian mountains (now eroded to their roots) that lay to the east, and were deposited in a narrow trough during the final stage in the filling of the Birrimian geosyncline. They consist of a non-auriferous basal conglomerate (Kawere conglomerate), overlain in sequence by the Banket series of quartzites and conglomerates, the Tarkwa chloritoid-bearing phyllites, and a thick upper series of impure quartzites (Huni sandstone). The Kawere conglomerate is believed to be the source of the alluvial diamonds extensively worked near Tarkwa, and a few small diamonds were recovered from a banket reef at Ashanti Adowsena mine, 100 miles north-east of Tarkwa.

In the Tarkwa goldfield, most of the banket series conglomerates are poorly sorted and some of them contain more fragments of Birrimian schist than quartz pebbles. Economic values rarely occur in such conglomerates and are generally restricted to relatively thin bands of silicified, well sorted and well packed, quartz conglomerate rich in black sand, occurring at or close to the base of the banket zone. The best and most persistent values are generally right at the base of the Basal reef or at the base of individual bands of conglomerate in this reef and in the overlying West reef. More than 90 percent of the 6 million ounces of gold won from the goldfield has been obtained from these two reefs in mines situated on or within two miles of the south-eastern outcrop of the banket.

It is believed that the paystreaks in the Basal and West reefs represent reconcentrations of gold from the reworking of originally lower grade gravels in rivers flowing from the east. It is unlikely that any appreciable amount of the gold in the bankets could have been derived from the Birrimian lodes of the Prestea-Konongo belt. On structural grounds, and also indirectly from the fact that the lodes have not been deeply eroded, it is believed that this belt was relatively low lying throughout the Tarkwaian. It is certainly true that the banket conglomerates in the western limb of the Tarkwaian synclinorium are poorly developed and contain very little gold.

Briefly, the evidence in support of the detrital origin of the gold is:

1. Its high average fineness (950 or more).
2. The intimate association of the gold with undoubtedly detrital black sand in which the original cross bedding is beautifully preserved.
3. The broad parallelism in the length down the dip of at least some of the pay shoots to the directions of the currents that transported the sediments.
4. The absence of structural controls of the orebodies, in contrast to the ubiquity of such controls in the lode deposits.
5. The extreme rarity of sulfides and carbonates in the bankets and wall rocks.
6. The rarity of gold in dikes, quartz veins, and faults, except in a few places at their contacts with payable banket. Away from the direct influence of the auriferous conglomerates, no gold occurrences of any interest are known in dikes, quartz veins, or faults anywhere in the Tarkwaian. In fact only one quartz vein in the Tarkwaian is reported to have produced any gold (600 ozs.), and this vein was only productive where it crossed a banket reef.

The local enrichments in faults and shears must have taken place after the bankets and wall rocks were silicified. They were partly due to secondary

migration of gold in shears along the richer than average footwall contact of the Basal reef and in faults displacing pay reefs.

As is the case in the Witwatersrand bankets, it is impossible to conceive how post-faulting selective epigenetic mineralization of the silicified conglomerates around folds and across faults and dikes displacing the conglomerates, could have taken place. A somewhat more plausible argument might be made out for pre-faulting and folding epigenetic mineralization, but the evidence as a whole would still favor a sedimentary origin for the gold.

If the iron-titanium ratio is a valid criterion for determining the origin of the mineralization in the Ghana bankets (Davidson, 1958, p. 887), it would not support the epigenetic theory as the average iron-titanium ratio (15:1) in analyses of bankets from five mines in Ghana, four of them in the Tarkwa goldfield, is very little different from the average ratio (13:1) in three analyses of other Tarkwaian sediments and 14:1 in nine analyses of the types of Birrimian rocks (argillites, graywackes and volcanics) from which the Tarkwaian was derived.

Very little is known about the occurrence of uranium in Ghana, apart from the results of scattered reconnaissance surveys by the U. K. Atomic Energy Division and the Ghana Geological Survey. It is true that the bankets worked in the mines at Tarkwa are essentially devoid of uranium, but apparently no systematic investigation of all the Tarkwaian conglomerates, either in the Tarkwa goldfield or elsewhere in Ghana, for uranium has been carried out.

N. R. JUNNER

MARLEY LANE, HASLEMERE,
SURREY, ENGLAND,
Aug. 25, 1959

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REVIEWS

SHORT REVIEWS OF NEW RUSSIAN BOOKS

Tekstury i struktury rud [Textures and structures of ores]. By A. G. Betekhtin, A. D. Genkin, A. A. Filimonova and T. N. Shadlun. Pp. 435; figs. 329 (mainly photomicrographs). Gosgeoltekhizdat, Moscow, 1958. Price 26r. 50k.

In this new work Academician Betekhtin and his associates have produced a quite outstanding volume on the mineragraphic study of ores, concerned not with the systematics of identification of the ore minerals (for which many good texts are already available) but rather with the interpretation of the history of ore deposits in the light of the evidence from the investigation of polished sections. After an introduction on the history of researches of this kind, there follow discussions on the crystallization of melts and solutions and on the properties of colloidal solutions and gels, a review of colloidal structures in ore deposits and their meaning, chapters on pseudomorphism and metasomatism, accounts of structures and textures arising from the break-down of solid solutions and also from the chemical decomposition of ore minerals, descriptions of cataclasis and plastic deformation in ores, and essays on the metamorphism of mineral deposits, on the sequence of mineralization in endogenetic ore-bodies, and on paragenetic relationships. The work closes with chapters on the systematization of mineragraphic studies, on the structures to be observed by the use of etching techniques, and on the practical applications of work of this kind. The range of examples discussed is wide, but it is clear that the authors have had a special interest in the study of platinoid deposits (Nizhne Tagilsk, Monchegorsk, Norilsk) and of uranium mineralization (ores from the Erzgebirge and from unspecified Russian localities). The work is excellently printed on heavy paper and is lucidly illustrated, but unfortunately as usual there is no index. An English translation would meet with widespread acceptance.

Geologiya rudnykh mestorozhdenii [Geology of Ore Deposits]. Bi-monthly from January 1959. Vol. 1, no. 1 (issued March 1959) Academy of Sciences, Moscow. Pp. 128; pls. 6. Price 12r. (about $2.00) each issue.

It is planned that this new bi-monthly periodical of the Academy of Sciences will cover much the same field in the U.S.S.R. as Economic Geology does in the West. The initial number comprises seven major papers, a few short mineralogical notes, and five reports of recent All-Union or International Congresses. Save for a table of contents in English the publication is wholly in the Russian language. The major papers include a short description of a large disseminated copper deposit in the Proterozoic sandstones of Udokansk, in the Olekmo-Vitimsk mountains of Yakutia, discovered in 1949; a good account of the copper-nickel sulfide deposits in the Pechenga (formerly Petsamo) mining field of the Kola peninsula; and a review of the tin deposits in extreme N.E. Asia. The journal, which is of a high standard, is edited by Academician Betekhtin with the collaboration of a board of distinguished economic geologists.

Boksity, ikh mineralogiya i genezis [Bauxites, their mineralogy and genesis]. Edited by N. M. STRAKHOV and G. I. BUSHINSKII. Pp. 488. Academy of Sciences, Moscow, 1958. Price 29r. 85k.

This well-produced work is divided into three parts: I, the mineralogy of bauxites (pp. 7–79); II, general questions on the genesis of bauxites (pp. 83–265); and III, the genesis of the bauxite deposits of the U.S.S.R. Twenty-eight authors have contributed 24 reports, some of them reviews of world literature but most being descriptive of the individual Russian occurrences. As in other Russian works much prominence is given to the views of Arkhangelsky on the sedimentary origin of many bauxite deposits, typical of these being the Devonian bauxites of the Urals which are notionally the aluminous analogues of oolitic iron ores into which they may sometimes merge. This sedimentary (marine, lacustrine and lagoonal) origin is attributed by extrapolation to some Western ore fields (those of Jamaica and Haiti, and of Arkansas in part) rather more dogmatically than most of their investigators would endorse. But the lucid and succinct accounts of the many Asiatic deposits make this Russian text a noteworthy contribution to the literature. A French translation is being prepared by the Bureau de Recherches Géologiques, Géophysiques et Minières.

Zakonomernosti razmeshcheniya poleznykh iskopaemykh [Regularities in the disposition of ore deposits]. Vol. I. Pp. 532, many (unnumbered) maps and plates. Academy of Sciences, Moscow, 1958. Price 43r.

In a compilation of 23 long articles an attempt is made to delineate the causal relationship between metallogenesis on the one hand and magmatism, tectonics and geological structure on the other. Among the more general contributions there are noteworthy papers by Kheraskov on the role of tectonics in relation to the localization of ore (76 pp.), by Kuznetsov on magmatic ore deposits, by Smirnov on regenerated ores and also on mercury deposits, and by Staritsky on the relation of magmatism to metallogenesis in platform provinces. Other articles refer to specific minerals or specific districts of the U.S.S.R., including among other topics mercury in Altai-Sayansk, titanium in Krasnoyarsk, the sulfide ores of the middle Urals, cobalt in the Caledonides of South-Central Siberia, the boron deposits of the Pacific province, and the phosphorite occurrences of the Soviet Union.

Materialy nauchnoi sessii po metallogenicheskim i prognoznym kartam [Contributions to the scientific session on metallogenetic and prognostic maps]. Pp. 319. Academy of Sciences, Kazakh SSR., Alma-Ata, 1958. Price 24r. 15k.

A symposium on the construction of metallogenetic and prognostic maps was held in Alma-Ata in December 1958, under the auspices of the All-Union and Kazakh Ministries of Geology and Academies of Sciences. The 24 articles preprinted in this volume of proceedings have a wide range, from discussions of the general principles that should govern the production of such maps as a basis for mineral exploration to accounts of the geological, geochemical and tectonic controls governing the distribution of various types of mineralization in several regions of the U.S.S.R. A third of the papers are concerned with the tin-tungsten ores, porphyry and "sedimentary" coppers, polymetallic deposits, rare metals and other mineralizations in central Kazakhstan. The papers on the distribution and genesis of the important tin and copper ore deposits are especially illuminating. The

Rhodesia-type copper mineralization very extensively developed in the Cambrian to Permian sediments of Dzhezkazgan is claimed to be of epigenetic origin, deriving from hydrothermal activity in Variscan times.

Taina Yakutskikh almazov [The secret of the Yakut diamonds], by M. S. ZRYAKOVSKII and N. N. MARKOV. Pp. 109. Gosgeografizdat, Moscow, 1958. Price 1r. 75k.

Skvoz' taezhnye debri [Through taiga forests], by M. BURENKOV. Pp. 84. Gospolitizdat, Moscow, 1958. Price 1r.

Siberian diamonds, by V. OSIPOV. Pp. 75. Foreign Languages Publishing House, Moscow, 1958. Price 30 cents. (Also in French and German.)

Several cheap paper-books, of which the above are typical, have appeared to glamorize the discovery and development of the Yakutian diamond fields. The young lady prospectors responsible for some of the initial discoveries are unexpectedly photogenic! To overcome the difficulties of milling in a region where the temperature falls to $-40°$ C, experiments are being conducted on methods of concentration using compressed air.

Geologiya Altaya [Geology of the Altai], by V. P. NEKHOROSHEV. Pp. 262. Gosgeoltekhizdat, Moscow, 1958. Price 14r. 25k.

After a brief introduction, pp. 15–177 cover stratigraphy, pp. 178–224 tectonics, and pp. 225–256 economic geology. There is only one illustration and although the extensive literature is well summarized the turgid sequence of page after page of stratigraphical detail makes dull reading.

Atlas karbonatnykh porod srednego i verkhnego Karbona Russkoi Platformy [Atlas of the carbonate rocks of the middle and upper Carboniferous of the Russian platform], by I. V. KHVOROVA. Pp. 170; pls. 67. Academy of Sciences, Moscow, 1958. Large quarto. Price 19r. 65k.

This inexpensive work consists of 397 photomicrographs of limestones and dolomites illustrated on 67 plates, accompanied by full petrographic descriptions. Introductory chapters provide a brief course of instruction on the petrography of carbonate rocks, a general conspectus of their classification and nomenclature, a petrographical classification specific to the Carboniferous strata of the Russian platform, and a review of the secondary changes which the rocks have undergone. The book is well printed in large type on heavy paper, and it is a pleasure to handle it.

C. F. DAVIDSON

UNIVERSITY OF ST. ANDREWS,
SCOTLAND,
Aug. 15, 1959

Crystal Structures, Supplement IV. By R. W. G. WYCKOFF. Pp. about 400, looseleaf to fit binders already issued; many figs. and tables. Reinhold Pub. Co., New York, 1959. Price $22.00.

This is actually the eighth issue of pages for a five-volume reference work that is to be completed by "Supplement V." Readers of ECONOMIC GEOLOGY should become aware of the whole work, for it contains within a stack of perhaps 2,200

pages already issued, a collection of outstandingly well-written, well-illustrated, and authoritative summaries of the crystal structures published to date. The work should be made known especially in research laboratories, for there its concise, easily understandable data can be most fruitfully applied to the study and beneficiation of ores.

The novel looseleaf binding arrangement makes it possible to issue the work over a period of several years, and still keep the earlier portions up to date with supplementary and replacement pages. However, this arrangement makes page numbers impossible over any extended portion of the book. The author's solution is to use four independent series of page-numbers in each chapter, one each for text, tables, illustrations, and bibliography. Supplementary and replacement material has been issued several times already. Every page has its complete designation showing chapter number, series, and page-number—for example, "Chap. V, text page 25," or "Chap. VIII, illus. page 1 (replacement)," or "Chap. X, table page 66 (supplement)." There is no difficulty in finding any particular mineral or other chemical compound if its formula is known, for the general table of contents shows the formula-types that will be found in the several chapters (as elements in Chapter II, formula-type RX_2 in Chapter IV, silicates in Chapter XII), and Table I in each chapter lists alphabetically the formulas of the crystals described, and constitutes the key to their locations in the chapter. "Supplement V" is to contain general indexes in addition.

The beautifully executed drawings showing spheres packed together in patterns illustrating the crystal structures are an outstanding feature of the book. Uniform tabulation of atomic coordinates affords precise data to accompany the illustrations, and the written text explains the interatomic relationships and calls attention to the similarities of pattern found in related crystals.

There are probably few practicing economic geologists who will need to refer often to the kind of information to be found in this work; but most would understand Wyckoff's explanations better, in many cases, than those of the original authors describing these structures. There certainly is no other equally concise and authoritative summary of the world's knowledge of crystal structures. This book is already well known to crystallographers; it should become better known to many others.

HORACE WINCHELL

Inženýrská geologie [Engineering Geology]. By Q. ZÁRUBA and V. MENCL. Pp. 486; figs. 358. Published by "Akademie," Praha, 1957.

Engineering geology has had a long and excellent tradition in Czechoslovakia. Due to the complexity of geologic conditions in that country, large engineering projects in the hydraulic and industrial fields, as well as modern highway and tunnel construction, have always required the most thorough geological investigation and studies.

In comparison with similar technical treaties, the textbook of "Engineering Geology" by Dr. Q. Záruba and V. Mencl brings new original concepts not only in the arrangement of the technical and scientific material but in its novel presentation. The material is divided into three sections.

The first section is dedicated to methods of geological research and investigation. In the introductory chapter the useful tasks and assignments of engineering geology are outlined in detail and co-operation between engineers and geologists is clearly defined. The following chapters of this section deal with the preparation

of geological maps and profiles and describe the various types of borings, as well as a complete summary of geophysical methods employed in engineering planning.

The second section analyzes particularly those characteristics of rocks and mineral deposits that influence their gradual disintegration, and stresses the importance of geological investigation for the opening of quarries and for the testing of foundations. Landslides and similar phenomena are treated in detail not only from purely geological standpoint but with due consideration to recent developments in soil mechanics. The third section is devoted to special application of geological studies to various branches of engineering construction (large industrial projects, transportation facilities, tunnels, dams and large water reservoirs).

The closing chapter refers to geological investigations for regional planning of new communities with a critical evaluation of the economic character of such investigations.

An important feature of this book is the great number of concrete examples supplementing the concise but well prepared text.

The book was soon sold out and in 1957 a second, enlarged edition was published. The book was translated into Rumanian and a German translation is now in preparation.

J. C. DOUCHA

SAN MATEO, CALIF.,
July 28, 1959

Die Entwicklungsgeschichte der Erde [The development-history of the Earth]. Pp. 722; figs. 229. F. A. Brockhaus-Verlag, Leipzig. Second edition, 1959. Price D.M. 13 ($4.00).

Students and teachers who read German will find in this elementary manual of geology a refreshing departure from the stereotyped ranks of text-book literature. Widely known throughout eastern Europe under its subsidiary title of "Brockhaus-Taschenbuch der Geologie," the manual is the work of no less than nineteen German geologists renowned in their respective spheres of specialization; and since it was first published in 1955 (the second edition is much enlarged) there has been a total printing of 45,000 copies. The scope is particularly wide and commendably up-to-date. After some introductory pages, an account of the internal structure and composition of the earth is followed by a brief introduction to mineralogy, chapters on the formation of the magmatic, sedimentary and metamorphic rocks, on soils, on weathering and its agents, earth movements due to internal forces, earthquakes, the structural deformation of the crust, and (27 pp.) on modern geotectonic hypotheses. The thirteen chapters on historical geology (with special emphasis on Germany and on Europe) occupy 158 closely printed pages, and are followed by highly condensed introductions to palaeontology (26 pp.), geological maps and mapping (8 pp.), isotope geology (12 pp.), applied geology (32 pp.), a chapter on rocks as constructional materials (16 pp.), and another on the history of geological studies (26 pp.). A comprehensive "ABC" or Encyclopaedia of Geology occupies the final 200 pages of text, and the book concludes with a 9-page bibliography of mainly German literature and a good index. As an introduction to Central European geology the work has much more than its low price to commend it.

C. F. DAVIDSON

UNIVERSITY OF ST. ANDREWS,
SCOTLAND,
August 14, 1959

The Earth Beneath the Sea. By FRANCIS P. SHEPARD. Pp. 275; figs. 113. Johns Hopkins Press, Baltimore, 1959. Price, $5.00.

This book by a well-known specialist in this field of investigation is aptly named. It deals with the 72 percent of the earth's surface that lies beneath the seas, where there are mountain ranges taller than the Himalayas and submarine trenches deeper than the Grand Canyon. The newest information regarding the sea bottom is set forth.

The material of the book can be readily grasped through the chapter headings: 1, Waves and Currents Modify the Sea Floor; 2, Catastrophic Waves from the Sea; 3, Our Transient Beaches; 4, The Continental Shelves that Surround the Lands; 5, Origin of Continental Shelves; 6, The World's Greatest Slopes; 7, Canyons of the Sea Floor; 8, The Deep-Ocean Floor; 9, Under the Ocean Bottom; 10, Coral Reefs and Their Undersea Wonderlands; 11, Using the Present Sea-Floor Deposits to Interpret the Past.

The book is written in a delightful manner to be enjoyed by any reader, and the accompanying illustrations make it even more appealing. The author brings to it his long personal knowledge of submarine geology and fuses scientific facts with the drama of the sea. Although any reader may enjoy it, there is also a wealth of scientific knowledge for the scientist.

The Upper Atmosphere. By H. S. W. MASSEY and R. L. F. BOYD. Pp. 333; illus. Philosophical Library, New York, 1959. Price, $17.50.

International Geophysical Year yielded much new knowledge regarding the earth, the oceans, and the atmosphere. This book deals with the phenomena of the upper atmosphere from studies made during the International Geophysical Year. It treats of the revelant physics, the atmosphere, research by balloons and rockets, probing with sound and radio waves, the ozonosphere and ionosphere, northern lights, aerial tides and magnetic effects, upper atmosphere disturbances, meteors, cosmic rays, and satellites. Present knowledge is outlined and the newer space projects are discussed. It is a book for scientists and students. The mathematical problems are indicated and some are obstruse. However, it is an authoritative reference for all interested in the upper atmosphere.

Man's Journey Through Time. By L. S. PALMER. Pp. 184; figs. 55. Philosophical Library, New York, 1959.

The title also states that this book is "A first step in Physical and Cultural Anthropochronology." The distinguished author is Professor Emeritus in the University of Hull, Yorkshire, and Honorary Curator of Wells Museum, Somerset.

Professor Palmer has gathered together evidence from the work of astronomers, geologists, physicists, pollen-analysts and carbon-fourteen investigators and shows how men have gradually developed in a million years from ape-like creatures to human beings. His first chapter deals with The Problem. Then follow Anatomical Evidence and Cultural Evidence and the Time Factor, involving various Evidences of Dating. The last chapter deals with Changes in Time. It is a fine story of pre-historic man, early man, his development to the present, and his probable trend in the atomic age of the future. It is nicely written, well illustrated, and pleasant reading.

Ozeane Salzlagerstätten. By HERMANN BORCHERT. Pp. 237; figs. 31. Gebrüder Borntraeger, Berlin, 1959. Price, D.M. 48.

This book is a discussion of oceanic salt deposits, their characteristics, origin and metamorphism. Its 20 chapters deal with deposition of salts, rhythmic sedimentation, temperature and dynamic conditions, load metamorphism, physical chemical conditions, primary and secondary facies changes, sequences, controls, metasomatic changes, different types of deposits, and relation between salt and petroleum. Practically every process entering into the formation of salt deposits, and the subsequent changes within them, are considered in detail. An extended bibliography of 40 pages is included.

To the student of salt deposits this is a very informative book.

Optical Mineralogy, 3rd Edit. By PAUL F. KERR. Pp. 442. McGraw-Hill Book Co., New York, 1959. Price, $8.50.

The first two editions of this well-known book were by Austin F. Rogers and the present author. The last edition appeared 16 years ago. Since that time the former senior author has passed away.

The general format of the previous edition has been retained, but the context has been thoroughly brought up to date. Many of the mineral descriptions have been revised and a number of new ones added. Also, selected references have been added, as have many new illustrations. The identification tables have been revised to make them more usable to identify unknown minerals. Although, as before, the text centers around thin section studies, now the descriptions and tables refer considerably to the use of mineral fragments.

Part I, of 10 chapters, takes up mineral preparation, the polarizing microscope, properties of light, refraction, polarized light, universal stage, properties of minerals, mineral fragments and identifications. Part II, with 5 chapters, deals with the different mineral groups and mineraloids and constitutes the main part of the book. Tables are provided to aid identification. The book is adequately illustrated; about one-half of the illustrations are new.

This edition includes all new data that have appeared since the predecessor edition, and the text has been revised to clarify the use of polarized light in the study of crystals.

With this revision the widely used book should continue to serve as a useful standard text and reference.

BOOKS RECEIVED

CYRUS W. FIELD AND JOHN E. COTTON

Zinc. Edited by C. H. MATHEWSON in cooperation with American Zinc Institute. Pp. 721. American Chemical Society Monograph 142. Reinhold Publishing Corp., New York, 1959. *"The science and technology of the metal, its alloys and compounds." Fourteen chapters containing 46 papers by 51 experts covering history, economics, geology, beneficiation, extraction, refining, processing, compounds, uses, marketing.*

Economics of Natural Resources Scarcity. Pt. I. H. J. BARNETT and CHANDLER MORSE. Pp. 146; figs. 4. Resources for the Future, Inc., Washington, D. C., 1959. *Chapters on "Contemporary Views on Social Aspects of Natural Resources,"*

"The First Conservation Movement," and the concepts of Malthus, Ricardo, Mill, Jevons, Darwin and Marsh.

The Assessment and Reduction of Risks in the Formation of an Oil Producing Company. MURRAY ALLAN BENNETT with JOHN J. SCHANZ, JR. Pp. 111; figs. 2. Pennsylvania State University, Dept. of Mineral Economics. Available through Independent Petroleum Association of America. *This Master of Science thesis scrutinizes the non-controllable and controllable risks characteristically encountered by oil companies.*

Beneficiation of Low Grade Manganese Ores of India. P. I. A. NARAYANAN and N. N. SUBRAHMANYAN. Pp. 182; figs. 53; tbls. 130; ch. 8. Price, Rs. 10=00. Council of Scientific and Industrial Research, New Delhi, India. *Manganese ores of India may be broadly classified into four groups—simple, complex, ferruginous, and garnetiferous. Most of the ores are amenable to beneficiation, and the concentrates are suitable for ferromanganese production.*

El Pais Tendra Su Ley Organica De Mineria. *A journal devoted to the mining industry of Argentina. Published monthly by Editorial Minera Argentina S. A., Dirección, Redacción y Administración, Buenos Aires.*

Problemas de Desenvolvimento Econômico de Pernambuco. FRANCISCO OLIVEIRA. Pp. 67; tbls. 14. Recife, Brazil, 1959. *Problems of economic development and concerned chiefly with agriculture.*

Rapports Annuels pour l'Année 1958 de la Section de Géologie, de Minéralogie et de Paléontologie du Musée royal du Congo belge et de la Commission de Géologie du Ministère du Congo belge et du Ruanda-Urundi. Pp. 32; fig. 1. Tervuren, 1959.

The Gold Deposits of the Cuyuni River. R. T. CANNON. Pp. 69; figs. 7. Colored geologic map in pocket scale, 1:125,000. Price, $1.00. Geological Survey of British Guiana Bulletin 27. *Discussion of geology, mines and production figures for this gold district.*

The Geology and Mineral Resources of the Jesselton-Kinabalu Area, North Borneo. P. COLLENETTE. Pp. 194; pls. 53; figs. 40; tbls. 22. Price, 14s. Geological Survey Department British Territories in Borneo Memoir 6, Sarawak, 1958. *This area consists of tertiary sediments associated with intrusive and extrusive igneous rocks. Of the twelve industrial rocks and minerals noted, only two, stone and clay, are currently utilized.*

A Review of the Sirenia and Desmostylia. ROY H. REINHART. Pp. 146; pls. 14; figs. 19; tbls. 18. University of California Publications in Geological Sciences, Vol. 36, No. 1, Berkeley and Los Angeles, 1959.

Geologic Map of California. San Luis Obispo Sheet. Scale 1:250,000. Price, $1.50. *State of California Division of Mines, San Francisco, 1958. Colored geologic map accompanied by separate sheet of explanatory data.*

Geology of the La Venta Badlands Colombia, South America. R. W FIELDS. Pp. 405–444, pls. 4, figs. 2; maps 2. Price, $1.00. Univ. of California Publications in Geological Sciences, Vol. 32, No. 6, Berkeley and Los Angeles, 1959. *Stratigraphy and structure of Mesozoic and Cenozoic sediments located in west central Colombia.*

Studies of Ice Excavation. DONALD O. RAUSCH. Pp. 90; figs. 57; tbl. 1. Price, $2.00. Quarterly of the Colorado School of Mines, Vol. 54, No. 2, Golden, 1959. *Discussion of the properties of ice, methods and problems of ice excavations, and the behavior of openings and their utilization.*

Annual Report for the Year 1958 Colony of Fiji. Pp. 18; pls. 7; figs. 4; tbl. 1. Price, 2s. Fiji. Paper 17, Legislative Council of Fiji, Suva, 1959. *Reconnaissance, regional, and detailed mapping has increased during the year. The first geological sketch map of the Fiji Islands was produced by S. R. M. Harvey.*

Le Synclinal de la Nyanga (Zone de la Boucle du Niari). Contribution a l'Etude des Minéralisations Stratiformes du Moyen-Congo. PIERRE NICOLINI. Pp. 178; pls. 12; figs. 22. Colored map in pocket, scale 1:500,000. Bulletin 10 de la Direction des Mines et de la Geologie, Afrique Équatoriale, Brazzaville, 1959.

Ignimbrite Bibliography. E. F. COOK. Pp. 30. Price, 25 cents. Idaho Bureau of Mines and Geology Information Circular 4, Moscow, 1959.

Natural Brines of Indiana and Adjoining Parts of Illinois and Kentucky. FRANK H. WALKER. Pp. 58; figs. 13; tbls. 20. Price, 75 cents. Indiana Geological Survey Rept. of Progress 13, Bloomington, 1959. *Preliminary report on the results of 473 brine analogies.*

Comité Spécial du Katanga Rapports et Bilans de l'exercice 1958. Pp. 168; pls. 8. Bruxelles, 1959. *Annual government report of financial expenditures and developments of the Belgian Congo. Included is a section for the mining industry. In French.*

Airborne Magnetometer and Scintillation Counter Survey Over Part of Johore and Malacca (Area 5). W. B. AGOCS. Geology by J. R. PATON. Summary by J. B. ALEXANDER. Pp. 54; separate map. Price, $5.00 Malayan. Federation of Malaya Geological Survey Econ. Bull. 1.5, Ipoh, 1959.

Bibliography of Geology of the Precambrian Area of Manitoba 1950–1957. W. S. BARRY. Pp. 39. Publication 57-3. Manitoba Department of Mines and Natural Resources, Winnipeg, 1959.

The Geology of Cook County Minnesota. F. F. GROUT, R. P. SHARP and G. M. SCHWARTZ. Pp. 163; pls. 16; tbls. 19; figs. 66. Price, $4.00. Bull. 39 Minnesota Geological Survey, Minneapolis, 1959. *An excellent and well illustrated report with chapters concerning the physical, general, glacial, historical, and economic geology of Cook County.*

New Mexico Streamflow and Reservoir Cortent 1888–1954. Pp. 326; figs. 8. New Mexico State Engineer Office Technical Rept. 7, Santa Fe, 1959. *A compilation in useful table form of over 100,000 separate items of basic hydrologic and climatological data.*

The Tectonic History of New Zealand. J. T. KINGMA. Pp. 55; figs. 11. New Zealand Geological Survey, Lower Hutt, 1959. Reprinted from New Zealand Journal of Geology and Geophysics, Vol. 2, No. 1, Feb., 1959. *The tectonic history of New Zealand is divided into two major periods, a late Mesozoic-early Tertiary phase and a late Tertiary-Quaternary phase.*

Hematitização e Alteração Ferruginosa no Granito das Beiras; sua Relação com Ocorrências de Urânio. J. ÁVILA MARTINS. Pp. 16; pls. 5. Memoria 16, Junta de Energia Nuclear, Lisbon, 1959. *Uranium occurrences in the Beiras granite massif are associated with brecciated quartz veins and red hematite-stained parts of the granite host rock.* In Spanish. Summaries in French and English.

Geološki Glasnik 1957. Pp. 190. Sarajevo, 1958.

The Wollastonite Deposit of Dirbat Well. M. L. KABESH and M. S. AFIA. Pp. 32; figs. 15. Republic of the Sudan Geological Survey Bull. 5, Khartoum, 1959. *Geology of the wollastonite deposits occurring in Precambrian metamorphic and igneous rocks.*

Notes on the Cainozoic History of Western Tasmania—"Malanna" Glaciation. M. R. BANKS and N. AHMAD. Pp. 117–127; figs. 4. Univ. of Tasmania Dept. of Geology Publication 73. Reprinted from Papers and Proceedings of Royal Society of Tasmania Volume 93, Hobart, 1959. *No evidences of Pleistocene glaciation has been found in Western Tasmania. Lewis's type area for the Malanna Phase.*

Geology, Mineral Resources, and Ground Water of the Cleveland Area, Tennessee. GEORGE D. SWINGLE. Pp. 125; figs. 8; tbls. 6; pls. 6. Tennessee Dept. of Conservation Bull. 61, Nashville, Tennessee. *Geology of a strongly folded and faulted terrain in the Appalachian Valley and Ridge province.*

Die Chrom- und Kupfererzlagerstaetten des initialen ophiolitischen Magmatismus in der Türkei. HERMANN BORCHERT. Pp. 175; figs. 11. Maden Tetkik ve Arama Enstitüsü Yayinlarindan, No. 102, Ankara, 1958. *Discussions of genetic conditions during formation of chrome and copper deposits and their regional occurrence.*

Bureau of Mineral Resources, Geology, and Geophysics—Melbourne, Australia, 1958–1959.

Bull. 37. The Maranboy Tin-field, Northern Territory. B. P. WALPOLE. Pp. 40; pls. 18; figs. 23; tbls. 5. *Only three of numerous cassiterite-bearing lodes may be expected to yield large tonnages of ore. These lodes occur in an inlier of Lower Proterozoic sediments surrounded by Cambrian and Cretaceous formations.*

The Australian Mineral Industry—Quarterly Review and Quarterly Statistics. Vol. 11, No. 4. Pp. 42; tbls. 17. Price, 3/-. *Review of imports, exports, and statistics of the mineral industry.*

Universidad de Chile Instituto de Geologia—Santiago de Chile, 1958.

Publ. 10. Sedimentos Cuaternarios y Aguas Subterraneas en la Cuenca de Santiago. JUAN KARZULOVIC KOKOT. Pp. 120; pls. 4; figs. 19; tbls. 10. *Geologic and hydrological study of the Santiago Valley.*

Publ. 11. Reconocimiento Geologico en la Parte S. W. de la Provincia de Atacama. JORGE MUNOZ CRISTI. Pp. 123–152; pls. 11. *Geology of the southwest part of Atacama Province. The marginal parts of the intrusive Andean Batholith exhibit phenomena attributed to granitization and anatexis.*

Publ. 12. 1. Reconocimiento Geologico de la Isla Mocha. JUAN TAVERA and CARLOS VEYL. **2. Petrografia de la Isla Mocha.** JORGE MUNOZ CRISTI. Pp. 157–196; pls. 10; figs. 24. *Two papers dealing with the stratigraphy and petrography of the Cenozoic sediments on Mocha Island.*

The Geological Survey of Taiwan—Taipei, 1959.

Bull. 10. Coal Resources of Taiwan. C. S. HO. Pp. 235; pls. 10; figs. 21; tbls. 2. *Present recoverable coal reserves total 209 million metric tons, which should be sufficient to meet present and expanded industrial requirements for the next five decades. English translation.*

A Biostratigraphic Study of the Miocene in Western Taiwan Based on Smaller Foraminifera (Part I: Planktonics). LI-SHO CHANG. Pp. 47–72; figs. 5; tbls. 4; pls. 5. *Description of foraminifera from Miocene sediments of Western Taiwan. Reprinted from Proceedings of the Geological Society of China No. 2, March, 1959.*

Akademie-Verlag Berlin—Germany, 1959.

C 60. Berg- und Hüttenmännischer Tag 1958 Geophysikalisches Kolloquium. Pp. 7–101; tbls. 12; figs. 71. *Nine papers relating to geophysics in the fields of mining and metallurgy.*

C 61. Die Bestimmung des Raumgewichtes von Böden und Gesteinen durch Gamma-Strahlen. KARL-HEINZ EIFE. Pp. 92; tbls. 12; figs. 92. *Discussion of theory and methods for calculating soil and rock densities utilizing gamma rays.*

C 65. Grundlagen und Auswerteverfahren der dynamischen Baugrundseismik. GÜNTHER BORNMANN. Pp. 100; tbls. 4; figs. 58. Price, 8.50 DM. *Theory and problems encountered utilizing seismic methods for determining structure.*

C 70. Geophysikalische Erkundung im Sudan. KLAUS SCHUSTER. Pp. 55; pls. 13; figs. 24. Price, 4 DM paper back. *Results of groundwater survey in the Sudan using seismic methods.*

Kommissionen for Videnskabelige Undersøgelser I Grønland—København, 1956.

Bd. 154, Nr. 1. Geologie der Nunatakker Region von Zentral-Oströnland Zwischen 72°30′ und 74°10′ N. Br. JOHN HALLER. Pp. 172; pls. 4; figs. 63; tbls. 7. Price, kr. 41.00. *The sedimentary series occurring in this region is difficult to correlate with the series in the fjord region because of alternation of facies. This is an area affected by Caledonia Tectonics. English summary.*

Bd. 154, Nr. 2. Die Strukturelemente Ostgrönlands Zwischen 74° und 78° N. JOHN HAILER. Pp. 27; pls. 11; figs. 2. Price, kr. 12.00. *In North and East Greenland the Archaen shield is surrounded by folded belts of Caledonian age. This orogenic belts strike parallel to the coast in this region. English summary.*

Bd. 154, Nr. 3. Der "Zentrale Metamorphe Komplex" von NE-Grönland. Tiel II. Die Geologische Karte der Staunings Alper und des Forsblads Jfordes. JOHN HALLER. Pp. 153; pls. 12; figs. 60; tbls. 4. Price, kr. 48.00. *The late- to post-Caledonian intrusive granites are regarded as late palingenetic products of the synorogenic migmatic activity. English summary.*

Idaho Bureau of Mines and Geology—Moscow, 1959.

Pamphlet 117. Geology of the Uranium Deposits near Stanley, Custer County, Idaho. B. F. KERN. Pp. 40; pls. 8; tbl. 1. *Fracture-controlled vein deposits and flat-lying deposits which are controlled both by fractures and favorable host rocks are considered to be of hydrothermal origin.*

Pamphlet 118. Geology and Mineral Resources of the North Fork Quadrangle, Lemhi County, Idaho. ALFRED L. ANDERSON. Pp. 92; pls. 10; figs. 4; tbl. 1. *This quadrangle having characteristics of both the Basin and Range and Northern Rocky Mountain provinces contains some gold, lead, thorium, and gravel, but they are receiving little attention.*

Indiana Geological Survey—Bloomington, 1958.

Bull. 15. Cement Raw Materials in Indiana. DUNCAN J. MCGREGOR. Pp. 88; pls. 2; figs. 3; tbls. 34. Geologic map in pocket, scale 1:1,000,000. *Discussion of areas in Indiana favorable for the future establishment of cement plants.*

Directory 6. Directory of Sand and Gravel Producers in Indiana. DUNCAN J. MCGREGOR. Pp. 53; figs. 4. *Includes brief summary of background, scope, and problems of this industry.*

Illinois Geological Survey—Urbana, 1959.

Circ. 270. Effects of Hydration Procedures and Calcination in the Presence of NaCl on the Properties of Lime Hydrates. D. L. DEADMORE and J. S. MACHIN. Pp. 33; pl. 1; figs. 20; tbls. 10. *Investigation of factors affecting the properties of lime putties.*

Circ. 271. Subsurface Geology and Coal Resources of the Pennsylvania System in Douglas, Coles, and Cumberland Counties, Illinois. KENNETH E. CLEGG. Pp. 16; pls. 3; figs. 3. *Limited subsurface data indicates the coal reserves of this area will not be of great economic importance.*

Circ. 272. Freeburg Gas Pool St. Clair County, Illinois. WAYNE F. MEENTS. Pp. 19; figs. 5; tbls. 3. *Geology and production statistics of recently discovered gas pool in southwestern Illinois.*

Circ. 273. Heavy Mineral Ratios of Sangamon Weathering Profiles in Illinois. JOHN A. BROPHY. Pp. 22; figs. 12; tbls. 2. *The open-textured Illinoian outwash was found to have been more weathered than Illinois till.*

Circ. 275. Stockpiling Illinois Coal for Coke. H. W. JACKMAN, R. L. EISSLER and R. J. HELFINSTINE. Pp. 14; figs. 6; tbls. 4. *Illinois No. 6 coal may be safely stockpiled during the summer if it is to be coked in a blend with medium-volatile coals or with a mixture of medium- and high-volatile eastern coals.*

Circ. 276. Electrokinetics. II. Development of Equations for Two-Phase Flow Through Single Capillaries. NORMAN STREET. Pp. 12; figs. 3. *A discussion of a theoretical flow pattern of two immiscible fluids, such as oil and water, through a porous medium.*

Circ. 277. Light-Burning Clay Resources in LaSalle County, Illinois. WALTER E. PARHAM. Pp. 27; figs. 3. *50 samples were run to determine the drying and firing shrinkage, water of plasticity, fired color, refractoriness, and bonding properties.*

Circ. 278. Coke from Medium-Volatile and Illinois Coals. H. W. JACKMAN, R. L. EISSLER, and R. J. HELFINSTINE. Pp. 24; tbls. 7. *Medium-volatile coals which are very fluid in the plastic state may be used to advantage in blends with Illinois coals to produce coke.*

Circ. 279. Mineral Production in Illinois in 1958. W. L. BUSCH. Pp. 43; figs. 9; tbls. 25. *Total value of minerals produced amounted to more than 603 million dollars; this is slightly lower than the total value in 1957.*

Educational Series 5. Guide to Rocks and Minerals of Illinois. Pp. 40; figs. 11; tbls. 2. Price, 25 cents. *Includes keys for identifying rocks and minerals.*

Rept. of Investigations 212. Acidic Structural Groups in Illinois Coals: Variation During Oxidation and Carbonization. T. P. MAHER, J. M. HARRIS, and G. R. YOHE. Pp. 75; figs. 31; tbls. 32. *Report on acidity changes occurring during the carbonization of coals.*

Geological Survey of India—Delhi, 1958.

Vol. XII. No. 3. Indian Minerals. Pp. 183–272. Price, Rs. 2 or 3 sh. *In addition to four papers in this issue, sections devoted to books reviews, notes and news, and mineral development and production are included.*

Vol. XII. No. 4. Indian Minerals. Pp. 273–358. Price, Rs. 2 or 3 sh. *Includes a review of field investigations during 1957–58 and the plans for the 1958–59 field season.*

Geological Survey of Japan—Hisamoto-chō, Kawasaki-shi, 1959.

Explanatory Text of the Geological Map of Japan. Koyasan (Kyōto-82). KEN HIRAYAMA and NOBUKAZU KAMBE. Pp. 48; figs. 28; tbl. 1. Map, scale 1:50,000. *This area is on the border of the Outer Zone of metamorphic rocks of Southwest Japan and the Inner Zone of Cretaceous and Cenozoic formations. In Japanese; English summary.*

Explanatory Text of the Geological Map of Japan. Hachijo-Jima (Hachijō-jima 5). NAOKI ISSHIKI. Pp. 63; pls. 4; figs. 19. Map scale 1:50,000. *Map of two volcanic islands; Ko-jima is one stratovolcanoe and Hachijō-jima is composed of two stratovolcanoes. In Japanese; English summary.*

Explanatory Text of the Geological Map of Japan. Kanita (Aomori-11). FUJIO UEMURA, KONROKU TSUSHIMA and MASATSUGU SAITŌ. Pp. 35; figs. 9; tbls. 2. Map, scale 1:50,000. *Oil seepages have been known in Neogene deposits, but prospecting has been unsuccessful. In Japanese; English summary.*

Explanatory Text of the Geological Map of Japan. Iyomisaki (Kōchi-67). TADASHI KIMURA and KŌJIRŌ KOMURA. Pp. 23; figs. 9. Map, scale 1:50,000. *Cupriferous pyritic deposits are mined from green schist formation in the Sambagawa metamorphic rocks. In Japanese; English summary.*

Geological Map and Explanatory Text of the Owada District, Rumoi Coal Field. Pp. 30; figs. 20; tbls. 5; pls. 7. *Two colored geological maps, scale 1:25,000 and 1:10,000 respectively. English summary of geology and properties of the Oligocene Owada coal-bearing formation.*

Colored geologic map of Karatsu, scale 1:200,000.

Kansas Geological Survey—Lawrence, 1959.

Bull. 134, Pt. 3. Sandstones of the Douglas and Pedee Groups in Northeastern Kansas. DONALD T. SANDERS. Pp. 125–159; pls. 2; figs. 5; tbls. 3. *These sandstones are interpreted as fillings of ancient river valleys.*

Bull. 134, Pt. 4. Germanium in Kansas Coals. JOHN A. SCHLEICHER. Pp. 161–179; figs. 2; tbls. 2. *No conclusions may yet be reached concerning geographic or stratigraphic variation in germanium content.*

Bull. 134, Pt. 5. Coal Resources of the Cherokee Group in Eastern Kansas. I. Mulky Coal. WALTER H. SCHOEWE. Pp. 181–222; pls. 6; figs. 6; tbls. 7.

Bull. 134, Pt. 6. Cross-Stratification, Dakota Sandstone (Cretaceous), Ottawa County, Kansas. P. C. FRANKS, G. L. COLEMAN, N. PLUMMER and W. K. HAMBLIN. Pp. 223–238; pls. 2; figs. 3; tbl. 1. *The source of sediments appears to have been to the northeast.*

Montana Geological Survey—Butte, 1959.

Bull. 12. Progress Report on Geologic Investigations in the Kootenai-Flathead Area, Northwest Montana. WILLIS M. JOHNS. Pp. 56; pls. 9; tbl. 1. *Emphasis is on the economic geology of numerous mineral deposits.*

Spec. Publication 18. Geologic map of the Northwest Flank of the Flink Creek Range, Western Montana. GEORGE E. MCGILL. Price, 40 cents. Scale, 1¾ inches : 1 mile.

New Zealand Geological Survey—Wellington, 1959.

Geological Map of New Zealand. Sheet 10, Wanganui. *Colored map, scale 1:250,000. Cenozoic marine and non-marine sediments cover the entire region.*

Bull. n.s. 35. The Geology of Motueka Subdivision. J. HENDERSON, E. O. MACPHERSON, and L. I. GRANGE. Pp. 26; fig. 1, tbls. 2. Price, 30s. *11 colored geologic maps in pocket. Stratigraphy, structure, physiography, and economic geology of a mountainous terrain.*

Northern Rhodesia Geological Survey—Lusaka, 1959.

Bull. 1. The Karroo System and Coal Resources of the Gwembe District, North-East Section. H. S. GAIR. Pp. 88; tbls. 4. Appendices 4; pls. 15. Maps, 2 scale 1:125,000. Price, £1 10s.

Records of the Geological Survey for the Year Ending 31st December, 1957. Pp. 20; pl. 1; tbls. 3; maps, 3. Price, 5s. *Four papers concerning regional and economic geology of selected areas in Northern Rhodesia.*

Annual Report for the Year 1958, Water Development and Irrigation Department. Pp. 7. Price, 1s.

Annual Report for the Year 1958, Department of Geological Survey. Pp. 8; fig. 1. Price, 2s.

Nyasaland Protectorate Geological Survey—Zomba, 1958–59.

Bull. 10. The Geology of the Middle Shire Area. S. W. Mcrel. Pp. 66; pls. 11; figs. 9; tbls. 4. Map in envelope. Price, 10/6. *While this area is not rich in economic minerals, there is considerable sulfide mineralization in the Mpemba pyroxenite intrusion and large vermiculite deposits near the Shire and Wankurumadzi Rivers.*

Annual Report of the Geological Survey Department for the Year Ended 31st December, 1958. Pp. 56. Price, 52-Od.

Oregon Department of Geology and Mineral Industries—Portland, 1959.

Bull. 49. Lode Mines of the Central Part of the Granite Mining District, Grant County, Oregon. George S. Koch, Jr. Pp. 49; figs. 25; tbls. 10. Price, $1.00. *Persistence of veins and relatively high gold content of some veins indicates continued but small mining ventures in the future.*

Bull. 50. Field Guidebook. Geologic Trips Along Oregon Highways. W. D. Wilkinson. Pp. 148; pls. 7; figs. 39; tbls. 4. Price, $1.50. *Includes an outline of the geology and mineral resources of Oregon, Cenozoic and Pre-Tertiary correlation charts for the state, and seven field trips.*

Ontario Department of Mines—Toronto, 1959.

Sixty-Sixth Annual Report, Vol. LXVI, Pt. 3, 1957. Geology of Cardiff and Faraday Townships. D. F. Hewitt. Pp. 82; pls. 14; figs. 3; tbls. 14. Map, 1 inch : ½ mile. *Cardiff and Faraday townships contain the main uranium mines of the famed Bancroft area. The major deposits are of the pegmatitic granite type and are usually accompanied by metasomatic replacement.*

Sixty-Seventh Annual Report, Vol. LXVII, Pt. 1, 1958. Pp. 81; figs. 4; tbls. 70. *The lead article, "Statistical Review of the Mineral Industry for 1957" by T. J. Kelly, reports that the value of production for 1957 increased 15 percent over the 1956 total to a new high of $760,041,556.*

Pennsylvania Geological Survey—Harrisburg, 1958–1959.

Atlas 167D. Geology of the Richland Quadrangle. Carlyle Gray, A. R. Geyer, and D. B. McLaughlin. Map, scale 1 in. : 500 ft. Text on the map. *The northern two-thirds of the map area lies in the Great Valley (Appalachian Valley Province) and the southern one-third, in the Triassic Lowland (Piedmont Province).*

Information Circ. 15. The Mineral Industry of Pennsylvania in 1957. Robert D. Thomson and Mary E. Otte. Pp. 39; fig. 1; tbls. 15. *Production statistics of the industry for 1957.*

Bull. C9. Geology and Mineral Resources of Bucks County Pennsylvania. B. Willard, J. Freedman, D. B. McLaughlin, and others. Pp. 243; pls. 24; figs. 30; tbls. 55. Two maps in separate cover. *Mineral resources (by H. R. Gault) include building stone, clay and clay products, lime, ocher, and sand and gravel.*

Bull. G31. The Annville, Myerstown and Hershey Formations of Pennsylvania. C. E. PROUTY. Pp. 47; pl. 1; figs. 19; tbl. 1; sections 9. *The above names have been applied to rocks formerly mapped as the "Leesport formation" by G. W. Stose.*

Serviços Geológicos de Portugal—Lisboa, 1958.

Tomo XL. Geology of the Goa District. Pp. 155; maps 3; figs. 13. *In Portuguese.*

Tomo XLI. The Geology, Petrology and Ore Deposits of the Vizeu Region, Northern Portugal. OEN YNG SOEN. Pp. 199; pls. 8; tbls. 4; figs. 19. Map in pocket, scale 1:50,000. *In English.*

Quebec Department of Mines—Quebec, 1959.

Geological Rept. 82. Dollier-Charron Area Abitibi-East and Roberbal Electoral Districts. E. R. W. NEALE. Pp. 46; pls. 8. Map in pocket, scale 1:63,360. *Geologic report for Precambrian terrain underlain by rocks similar to those of the adjacent Chibougamau District.*

Geological Rept. 83. Queylus Area Abitibi-East and Roberval Electoral Districts. P.-E. IMBAULT. Pp. 37; pls. 4. Map in pocket, scale 1:63,460. *Geologic report for Precambrian terrain south of the Chibougamau District.*

Geological Rept. 84. Fancamp-Hauy Area Abitibi-East Electoral District. STANLEY W. HOLMES. Pp. 33; pls. 8; figs. 2. Map in pocket, scale 1:63,360. *Description of Precambrian igneous and metamorphic terrain with nickel-copper and gold prospects.*

Geological Rept. 85. Brongniart-Lescure Area Electoral District of Abitibi-East. H. B. LYALL. Pp. 29; pls. 3. Map in pocket, scale 1:63,360. *Geology of a dominantly igneous and metamorphic terrain south of the Chibougamau Copper district.*

Tanganyika Geological Survey—Dar es Salaam, 1958–1959.

Bull. 29. The Geology of the Nyanzwa Area Quarter Degree Sheet 63 NW. J. K. WHITTINGHAM. Pp. 27; pls. 2. Map in pocket, scale 1:125,000. *Stratigraphy, structure, petrology, geomorphology, hydrology, and economic geology of the Nyanzwa area. Commercial quantities of mica occur in pegmatites, some of which are currently being worked.*

Short Paper 24. Geology and Gold Deposits of the Ruvu River Area. B. N. TEMPERLEY. Pp. 37; pls. 7; figs. 2; maps 3. Price, 10/-. *The alluvial gold is believed to have been derived from pyritic quartz veins.*

Quarter Degree Sheet 53 N.E. Mlali. Scale, 1:125,000. *Brief description of the geology of this dominantly Precambrian terrain on map margin.*

Uganda Geological Survey—Entebbe, 1959.

Rept. 1. The Geology of Southern Mengo. J. W. PALLISTER. Pp. 124; figs. 24. Maps in pocket, scale 1:100,000. Price, Shs. 50. *Swamps and a thick lateritic soil cover in this lowland have curtailed extensive mineral exploration. Pegmatites have been worked for several minerals, but most metal occurrences noted by this survey are not of commercial grade.*

Records of the Geological Survey of Uganda 1955–56. Pp. 50; pls. 4; figs. 9; tbls. 2. Price, Shs. 7/50. *Five papers dealing with geomorphology, petrology, and geophysical and geochemical prospecting.*

Western Australia Geological Survey—Perth, 1958–1959.

Bull. 6. The Gypsum Deposits of Western Australia. L. E. DE LA HUNTY and G. H. LOW. Pp. 110; tbls. 7; pls. 6. *Discussion of mining methods, production, and reserves of gypsum in Western Australia.*

Bull. 111. The Exploratory Diamond Drilling of the Koolyanobbing Iron Deposits for Pyrite. H. A. ELLIS. Pp. 140; tbls. 23; pls. 2. *Excessive milling costs due to the fine grained nature of the pyrite may prevent utilization of these deposits in the near future.*

Government Chemical Laboratories Report for the Year 1957. Pp. 16; tbls. 7. *Summary of activities for the various laboratory divisions.*

West Virginia Geological Survey—Morgantown, 1959.

Bull. 16. Oil and Gas Report and Map of Doddridge and Harrison Counties, West Virginia. OSCAR L. HAUGHT. Pp. 39; figs. 3. Map, scale 1:62,500.

Rept. of Investigations 17. High-Alumina Clays of West Virginia. WALTER A. TALLON *and* RICHARD G. HUNTER. Pp. 49; pls. 8; figs. 5. *Combination clay-coal mines might permit both sub-marginal deposits to be mined profitably.*

U. S. Atomic Energy Commission—Washington, D. C., 1959.

TID-8200. Nuclear Reactors Built, Building or Planned in the United States as of June 30, 1959. Pp. 32; tbls. 6. *Report list pertinent data for all nuclear reactors.*

TID-8506. Costs of Nuclear Power. Pp. 29; tbls. 2; fig. 1. Price, 50 cents.

Economic Geology
Vol. 54, 1959, pp. 1340–1362

SOCIETY OF ECONOMIC GEOLOGISTS

MEETINGS

The Society will meet at the Penn-Sheraton Hotel, Pittsburgh, Pennsylvania, November 1–4. The Program will be as follows:

Sunday Afternoon, November 1

Symposium, Allegheny Room, Penn-Sheraton Hotel
The Role of Stable-Isotope Research in the Field of Ore Deposits
H. L. James, Moderator
Opening Remarks, J. L. Gillson, President of SEG

1. 2:00 H. L. James: General features of stable-isotope research as applied to problems of ore deposits. Introduction.
2. 2:20 A. E. J. Engel: Review and evaluation of studies of the O^{18}/O^{16} ratio in mineral deposits.
3. 2:40 Donald E. White * and Harmon Craig: Isotope geology of the Steamboat Springs area, Nevada.
4. 3:00 R. S. Cannon, Jr.*, A. P. Pierce, and J. C. Antweiler: Significance of lead isotopes to problems of ore genesis.
5. 3:20 F. D. Eckelmann and J. L. Kulp *: Lead isotopes and ore deposition in in the Southeast Missouri lead district.
6. 3:40 John S. Brown * and F. G. Snyder: Discussion of lead-isotope data for Southeast Missouri.
7. 4:00 V. Rama Murthy: Lead-isotope study of ore and igneous minerals at Butte, Montana.
8. 4:20 M. L. Jensen: Summary: Sulfur isotopes and economic geology.

Time for discussion will be allowed after each paper.

The Sunday afternoon session will be followed by a social hour (5:30–6:30) in the Monongahela Room, Penn-Sheraton Hotel, and a dinner (6:30–8:00) in the same room after which the technical discussions will be resumed with Thomas S. Lovering as moderator.

Tickets for the dinner are $5.00 each. They may be obtained from the Secretary, GSA by pre-registration or they may be purchased at the GSA registration desk at the Penn-Sheraton Hotel.

Non-members are welcome to attend.

Monday Morning, November 2, Urban Room

D. F. Kidd and J. P. Pollock, Cochairmen
(After each paper 5 minutes is allowed for discussion)

1. 9:00 Robert Schneider * and Harry G. Rodis: Aquifers in meltwater channels along the southwest flank of the Des Moines lobe, Lyon County, southwestern Minnesota.

* Indicates speaker.

2. 9:20 William Hack: Application of the concept of facies to chemical aspects of ground water.
3. 9:40 E. Wm. Heinrich and Charles A. Salotti *: Copper-zinc skarn deposits in south-central Colorado.
4. 10:00 Robert O. Fournier: Mineralization of a portion of the porphyry copper deposit near Ely, Nevada.
5. 10:20 Henry Lepp * and Samuel S. Goldich: Chemistry and origin of iron formations.
6. 10:40 C. L. Jones: Potash deposits in the Carlsbad district, southeastern New Mexico.
7. 11:00 Duncan R. Derry: Evidence of the origin of Blind River uranium deposits—a progress report.
8. 11:20 A. M. Abdel-Gawad and Paul F. Kerr: Basal Chinle silicification.
9. 11:35 Alfred H. Truesdell * and Alice D. Weeks: Relation of the Todilto limestone uranium deposits to Colorado Plateau uranium deposits in sandstone.
10. 11:50 J. D. Love and Charles Milton *: Uranium and phosphate in the Green River formation of Wyoming.

Monday Afternoon, November 2, Urban Room

A. E. J. Engel and A. E. Buller, Cochairmen
(After each paper 5 minutes is allowed for discussion)

1. 2:00 A. F. Hagner and L. G. Collins *: Host rock as a source of iron, Ausable Forks magnetite district, New York.
2. 2:20 Herbert R. Shaw: Phase studies in the Fe-rich carbonates of the Bunker Hill mine, Idaho.
3. 2:40 J. E. Gill: Solid diffusion and volatility of sulfides—some experimental results.
4. 2:55 Duncan McConnell: Economic significance of the biogeochemistry of carbonate apatites.
5. 3:15 J. Kalliokoski: Sphalerite temperatures from the Brunswick and Nigadoo deposits, New Brunswick, Canada.
6. 3:35 Arthur W. Rose: Trace elements in sulfide minerals from the Central district, New Mexico, and the Bingham district, Utah.
7. 3:55 Edwin Roedder: Fluid inclusions as samples of the ore-forming fluids.
8. 4:10 R. K. Wanless,* R. W. Boyle, and J. A. Lowdon: Sulfur-isotope investigation of the gold-quartz deposits of the Yellowknife region, N. W. Territories, Canada.
9. 4:25 E. W. C. Dechow * and M. L. Jensen: Sulfur isotopes and the origin of the Heath Steele ore deposits, New Brunswick, Canada.
10. 4:40 Jules D. Friedman: S^{32}/S^{34} isotopic abundance ratios and genesis of sulfide ore bodies at Summitville and Ellenville, New York.
11. 4:55 Motoaki Sato: An electrochemical study of oxidation of sulfide minerals at 25° C.

* Indicates speaker.

To be read by title

G. C. Amstutz: Time criteria in ore genesis: a revision.

Charles L. Dahl and Mathew P. MacKowski: Trace ferrides in iron ores from the Iron Springs District, Utah.

David A. Duke and Frank H. Howd: Jasperoid and ore deposits in the Tintic and East Tintic Districts, Utah.

John Lemish: Measurement of pore size distribution in some hydrothermally altered wall rocks.

Edwin V. Post: Silica cemented sandstone as a guide to unoxidized uranium deposits in the Southern Black Hills, South Dakota.

James C. Warman and Lauson V. Causey: Groundwater from springs in Calhoun County, Alabama.

Kamble Widmer: Jointing with relation to groundwater movement in the Triassic rocks of New Jersey.

HAROLD M. BANNERMAN
Secretary

SYMPOSIUM PAPERS—ABSTRACTS

GENERAL FEATURES OF STABLE ISOTOPE RESEARCH AS APPLIED TO PROBLEMS OF ORE DEPOSITS: INTRODUCTION

HAROLD. L. JAMES

U. S. Geological Survey, Menlo Park, California

Application of the studies of stable isotopes is still in its infancy, but the results to date hold great promise of providing new methods of attack on some very old problems of economic geology. Measurements of oxygen isotopic ratios of various minerals, particularly quartz, carbonates, and magnetite, may provide geologic thermometers and perhaps clues as to the nature and origin of some ore-forming fluids. The isotopic composition of sulfur in sulfides and of hydrogen, oxygen, and carbon in thermal waters and fluid inclusions of ore minerals similarly may provide controls on concepts of ore-depositing solutions. The measurements of lead isotopes furnish a basis for fundamental studies of primordial metal distribution in the crust and, for ore deposits, a nongeologic means of differentiating between deposits that originated by magma fractionation and those derived by aggregation of metals from rocks traversed by hydrothermal solutions.

GENERAL FEATURES OF STABLE-ISOTOPE RESEARCH AS APPLIED TO PROBLEMS OF ORE DEPOSITS

HAROLD L. JAMES

The number of qualified isotope geochemists available for this type of work is small, the equipment is costly, and many of the extractions and measurements are difficult and time-consuming. This expenditure can be justified and this limited capacity properly exploited only if economic geologists and petrologists are willing to put equivalent or greater effort into defining the field problems, into proper selection of materials, and into the exceedingly complex problem of geologic interpretation of the results.

REVIEW AND EVALUATION OF STUDIES OF THE O^{18}/O^{16} RATIO IN MINERAL DEPOSITS

A. E. J. ENGEL

California Institute of Technology, Pasadena, California

Knowledge of the variations in the ratio O^{18}/O^{16} in minerals and entrapped fluids of ore deposits and their wall rocks, if coupled with thoughtful field studies, will contribute to our understanding of (1) the physical and chemical environment of ore formation, (2) the amount, kind, and source of any large volumes of oxygen-bearing fluids associated with ore genesis, (3) the scope and interrelations of supergene, hypogene and sedimentary processes and (4) the paragenesis of minerals in the deposits.

Variations in the isotopic composition of oxygen seem especially useful in defining the temperature of growth or of recrystallization of oxygen-bearing minerals, the degree of chemical equilibrium approached during crystallization, and the extent to which magmatic or metamorphic fluids may have been mingled with meteoric waters.

Studies of the variations of O^{18}/O^{16} in some alteration zones enveloping and genetically related to ore, if complemented with field and other laboratory studies, may prove useful as a guide to ore.

Although work done to date suggests this enormous potential value of oxygen isotope studies, the lack of follow-up of these studies seems to indicate the scarcity of skilled and interested personnel and of physical resources in research geology. Perhaps this is largely related to the fact that too many of us are interested in mineral deposits largely as a source of income rather than as fascinating phenomena to be understood.

ISOTOPE GEOLOGY OF THE STEAMBOAT SPRINGS AREA, NEVADA

DONALD E. WHITE AND HARMON CRAIG

U. S. Geological Survey, Washington, D. C. and Scripps Institution of Oceanography, La Jolla, California

Deuterium/H, Tritium/H, O^{18}/O^{16}, and C^{13}/C^{12} ratios of thermal and surface waters, together with geological and chemical evidence, greatly clarify the complicated hydrologic relations of the Steamboat Springs volcanic hot springs area. The major streams have characteristic differences in Deuterium O^{18}, and C^{13}, depending on details of origin, evaporational history, and probable influence of organic carbon from soils.

All thermal waters so far studied, from volcanic areas of abnormally high heat flow in North America, Iceland, and New Zealand, are closely related isotopically to meteoric waters of each particular area, and these meteoric waters generally differ significantly. Qualitatively this proves that each thermal water is dominantly meteoric.

Steamboat Springs water is probably from the Carson Range west of the springs. Steamboat Creek, draining from Washoe Lake to the south, and streams from Virginia Range to the east, are improbable sources of recharge. O^{18}/O^{16} of thermal water is increased by exchange with "heavy" oxygen of silicates, and is probably related to hydrothermal alteration. Most meteoric water is more than 30 years old but thermonuclear tritium contamination proves existence of minor local recharge,

with travel times of several months. Water of volcanic origin probably constitutes less than 5 percent, and perhaps less than 1 percent of the total.

Connate and, with little doubt, magmatic and metamorphic waters differ isotopically and chemically from ordinary surface waters. Through studies of waters and solid phases, it may become possible to interpret physical environments of epithermal ore deposits and determine relative influences of waters of different origins.

THE SIGNIFICANCE OF LEAD ISOTOPES TO PROBLEMS OF ORE GENESIS

R. S. CANNON, JR., A. P. PIERCE AND J. C. ANTWEILER

U. S. Geological Survey, Denver, Colorado

Searching questions about the origins of ore deposits have been asked for many years. Where do ore-fluids originate—within the crust, or deeper? Can specific sources of ore-metals be identified? When were ores deposited? How long did mineralization continue? What was the rate and paragenesis of deposition? Which deposits are cogenetic, and what metallogenetic provinces do they define? Lead-isotope studies offer hope of obtaining some answers. Analyses of lead from rocks and ores, being made at about 20 laboratories, have begun to suggest partial answers and raise new questions.

Ore-lead, as shown several decades ago, ranges widely in isotopic composition. Recent studies show that traces of lead in ordinary rocks of the earth's crust exhibit apparently similar variations. All of these variations are attributable primarily to mixing of old lead with accumulations of new radiogenic lead from uranium- and thorium-decay. Each individual sample of lead preserves in its isotopic composition a record of its own mixing history. This constitutes a composite record of the time this lead spent in different environments, its past associations with uranium and thorium, and the geochemical processes that moved it from place to place.

Integrated study of all these variables will throw light on many difficult problems of ore genesis when adequate techniques are developed. But progress will be slow until more accurate lead-isotope analyses can be made at lower cost and more objective criteria developed for interpreting measured isotopic compositions in terms of geologic history.

LEAD ISOTOPES AND ORE DEPOSITION IN THE S.E. MISSOURI LEAD DISTRICT

J. L. KULP* AND F. D. ECKELMANN

Lamont Geochemical Laboratory, Columbia University, and Department of Geology, Brown University

The Pb^{206}/Pb^{204} ratio in galena samples from the Southeast Missouri district ranges from 19.56 to 26.26 and appears to be due to variations in the radiogenic lead component of source solutions. At the Bonne Terre Mine where the geologic relationships are relatively simple and maximum isotopic data are available, the lead isotopic composition near ore channels is most radiogenic. In stratigraphically higher horizons and greater distances from the point of ore introduction the deposit

* Indicates speaker.

contains progressively less radiogenic lead reflecting the sequential deposition of ore. The age of the source environment appears to be about 1400 m.y. based on the lead isotopic data and a Rb-Sr age determination. The most probable mechanism for the formation of ore solutions appears to be inhomogeneous extraction of the lead from granitic rocks in the basement resulting, in the simple cases, in ore solutions with gradually increasing ratio of common rock lead/radiogenic lead.

The clear relationships between lead isotopic composition and the distribution of the ore around an ore channel in Bonne Terre make it possible to suggest the location of ore channels and mineralization history in other parts of the Lead Belt where the geology is more complex.

DISCUSSION OF LEAD ISOTOPE DATA FOR SOUTHEAST MISSOURI

JOHN S. BROWN * AND F. G. SNYDER

St. Joe Lead Co., Bonne Terre, Mo.

In a large measure the authors concur with Eckelmann and Kulp as to the pattern of isotope variation developed by this investigation and its significance as to the source region and direction of travel of ore solutions. These clearly seem to have risen through the basement and dispersed upward and outward as they were deposited in the sedimentary cover.

There is genuine disagreement, however, as to the time relations of more and less radiogenic lead. Several well distributed and clearly geologically dated samples show the more radiogenic lead to be definitely deposited last. In the authors' opinion this necessitates some fundamental revision of the proposed mechanism of source, derivation and deposition processes.

LEAD ISOTOPIC STUDY OF ORE AND IGNEOUS MINERALS AT BUTTE, MONTANA

V. RAMA MURTHY

Division of Geologic Sciences, California Institute of Technology, Pasadena, California

Isotopic composition of lead in the ores and igneous rocks at Butte indicates that the relation between ores and associated igneous rocks is far more complex than is generally assumed for a simple hydrothermal ore deposit. The lead in the quartz monzonite is distinctly more radiogenic than the lead in the ore. The rock and ore leads may be derived either from two different sources, or, they represent different mixtures of at least two types of leads. Hence, in this case, the parental relationship of igneous rock to the ore is doubtful.

The isotopic composition of lead in feldspar either from the igneous rock or pegmatites is dependent upon the degree of alteration of feldspar. The less altered feldspar has lead with a composition closer to that of the rock, whereas the more altered feldspar lead resembles that of ore. This dependency of the composition of lead on the degree of alteration is interpreted as due to the mixing of original feldspar lead with ore lead introduced into the feldspar at the time of alteration.

The relation between the ores and sedimentary rocks of Precambrian and post Precambrian age in the Butte area is discussed. The ore lead at Butte is classified as a B-type anomaly. Mechanisms by which such an anomaly can be caused are discussed.

A SUMMARY: SULFUR ISOTOPES AND ECONOMIC GEOLOGY

M. L. JENSEN

Department of Geology, Yale University, New Haven, Conn.

Sulfur isotopic studies have been useful as an economic geology "tool" because of the ubiquity and extensive isotopic fractionation of sulfur.

Sulfur from troilites exhibits a remarkably uniform S^{32}/S^{34} composition of 22.21 ± 0.02 ($\delta S^{34} = 0.0$ permil). Assuming that primordial earth sulfur had a similar composition, geologic processes have caused δS^{34} values for sulfides alone to vary between $+40.1$ to -52.0%.

Some observations made of the significance of δS^{34} studies are:

1. Sulfides from magmatic hydrothermal deposits exhibit a very narrow spread in δS^{34}, generally near the troilite value.
2. Sulfides from hydrothermal deposits not associated with an intrusive source exhibit a broad spread in δS^{34}.
3. Nonequilibrium reduction of $SO_4^=$ to H_2S by anerobic bacteria results in a variable enrichment of S^{32} in the H_2S formed. This effective reducing agent can cause the concentration of numerous constituents such as U, Fe, and Cu, as it apparently has done in the formation of some epigenetic deposits where ore-bearing solutions have encountered this gas such as sandstone-type uranium deposits and "Red Beds" copper deposits, and in the formation of syngenetic sulfides including possibly the Rhodesian Copper Belt.
4. Inorganic reduction of $SO_4^=$ to $S^=$ is quite rare. The abundance of carbon, however, with many of the New Brunswick, Canada, sulfides suggests the possibility of reduction of $SO_4^=$, enriched in S^{34}, at high temperatures forming, therefore, sulfide deposits enriched in S^{34}.
5. Oxidation of $S^=$ to $SO_4^=$ in hypogene solutions may be the cause of S^{34} enrichment in hypogene sulfates; in contrast, no detectable isotopic fractionation occurs during supergene oxidation.

AQUIFERS IN MELTWATER CHANNELS ALONG THE SOUTHWEST FLANK OF THE DES MOINES LOBE, LYON COUNTY, SOUTHWESTERN MINNESOTA

ROBERT SCHNEIDER AND HARRY G. RODIS

U. S. Geological Survey, St. Paul, Minn.

During the Cary and Mankato substages of Wisconsin glaciation the Des Moines lobe advanced southeasterly through the broad lowland of the Minnesota River valley of southwestern Minnesota, and thence southward to central Iowa.

Among the most prominent topographic features in Lyon County, Minn., are five northwest-trending end moraines, two of which are associated with and parallel to belts of surficial outwash which are approximately half a mile to a mile wide. Test drilling indicated that one of the belts of outwash is underlain by a complex system of buried meltwater channels. The other is the upper part of a series of deposits in an incised channel. The channels are filled with till, glaciolacustrine deposits, and outwash which includes permeable deposits of water-bearing sand and gravel.

Associated with the surficial meltwater channels is a pronounced north-west-trending linear drainage pattern. By studying the lineation of streams and lakes,

analyzing the available water-well data, and drilling test holes, several elongate deposits of buried outwash having little or no topographic expression were located. The long axes of the deposits are generally parallel to the lineation of the drainage and the end moraines.

The meltwater channels in Lyon County trend northwest-southeast because the flank of the ice sheet was confined by a landmass that sloped to the northeast. By studing their local occurrence, it is probable that other buried channels can be located and additional ground-water supplies developed elsewhere along the southwest flank of the Des Moines lobe.

APPLICATION OF THE CONCEPT OF FACIES TO CHEMICAL ASPECTS OF GROUND WATER

WILLIAM BACK

U. S. Geological Survey, Washington 25, D. C.

The notion of facies provides the conceptual model for explaining the distribution and genesis of the principal chemical types of ground water in the Cretaceous and Tertiary formations in the northern portion of the Atlantic Coastal Plain. Significant parameters of these hydrochemical facies can be illustrated by methods similar to those used in lithofacies studies—trilinear diagrams, isometric panel diagrams, and maps showing lines of equal concentrations of individual constituents or concentration ratios of various constituents.

The development of hydrochemical facies can be thought of as a chemical response to the interrelated effects of the lithology and flow pattern of the hydrologic system. Within the Coastal Plain sediments the calcium magnesium bicarbonate facies occurs in areas of high head; the sodium bicarbonate facies occurs in downgradient areas of lower head. Laboratory data on ion-exchange capacities indicate that glauconite, kaolinite and montmorillonite are the controlling materials that bring about these changes. The distribution of the sodium chloride facies in the Cretaceous sediments may be controlled by piezometric highs underlying higher landmasses in Maryland and New Jersey. Mapping of these facies demonstrates that the outcrop area of the Cretaceous and Eocene sediments in southern Maryland and southern New Jersey functions as a discharge area for ground water, rather than a recharge area as is more normally the role of the outcrop of artesian aquifers.

Publication authorized by the Director of the U. S. Geological Survey.

COPPER–ZINC SKARN DEPOSITS IN SOUTH-CENTRAL COLORADO

E. WM. HEINRICH AND CHARLES A. SALOTTI

Department of Mineralogy, The University of Michigan, Ann Arbor

A number of geologically and mineralogically similar copper-zinc skarn deposits that occur from Salida to the Colorado Front Range have been reexamined. Of these, the most famous is the Sedalia mine described by Lindgren in 1907. Two deposits, the Betty, near Guffey, and the Cotopaxi, just northwest of Cotopaxi, have been studied in detail. Paragenetic studies on Cotopaxi skarns serve also to illustrate the nature of the mineralization in the other deposits.

The Cotopaxi is an irregular lens, about 300 by less than 50 feet in size, set in a 1½ by 2 mile xenolith of Idaho Springs rocks within Pikes Peak granite. Mineralization is confined to an amphibolite layer between hanging wall biotite gneiss and footwall sillimanite gneiss. During Stage I of the development of the deposit the amphibolite was reorganized into coarse foliated aggregates of anthophyllite, actinolite, garnet, thulite, clino-humite, forsterite, and scapolite. This phase was succeeded by the generation of a pegmatoid of quartz, oligoclase, garnet, phlogopite and gahnite. In the third (ore) stage, molybdenite (minor), sphalerite, chalcopyrite, pyrite and galena replaced the skarn species and filled fractures. During the final stage chlorite and sericite replaced earlier high temperature silicates. In contrast to Lindgren, who believed the deposits to be magmatic in character, the geology and mineralogy suggest a pyrometasomatic environment in rocks of high grade metamorphic character.

MINERALIZATION OF A PORTION OF THE PORPHYRY COPPER DEPOSIT NEAR ELY, NEVADA

ROBERT O. FOURNIER

Department of Geology, University of California at Berkeley, U. S. Geological Survey, Washington 25, D. C. (present address)

The geology of the Liberty open pit copper mine was mapped in detail. The original textures of ore-bearing porphyritic rocks were similar to one another, but differed markedly in groundmass texture from non-sulfide-bearing prophyritic rocks in the district. In one area of the pit the injection of igneous material appears to have taken place simultaneously with economic mineralization and alteration. A sericite alteration of plagioclase in one rock preceded the intrusion of a second rock in which the plagioclase is altered to montmorillonite. The primary copper content of the first rock is several tenths of a percent higher than that of the second rock. Most chalcopyrite is distributed as grains in the groundmass with no trace of alignment along previously existing cracks. Other chalcopyrite grains are found along cracks "healed" by quartz and K-feldspar. Small amounts of chalcopyrite are along "unhealed" cracks.

In another portion of the pit a large porphyry body exhibits a concentric zonal alteration pattern related to fissures and pyrite-bearing veins. The outermost zone contains kaolinite after plagioclase and black biotite after hornblende. An intermediate zone contains recrystallized brown biotite (magnesium-rich eastonite) with sericite or sericite plus K-feldspar replacing only plagioclase. In the innermost zone the only silicates are quartz and a magnesium-rich dioctahedral mica.

THE CHEMISTRY AND ORIGIN OF IRON FORMATIONS

HENRY LEPP AND SAMUEL S. GOLDICH

University of Minnesota, Duluth, Minnesota; Minneapolis, Minnesota

The Fe content of 15 comparatively unaltered iron formations, Keewatin (> 2.6 b.y.) to Jurassic in age, ranges from 25.4 to 35.0 weight percent as is indicated in published analyses. The other major constituents are SiO_2, CaO, MgO, and CO_2. Silica and carbonate contents vary inversely.

Cherty iron formations of great thickness and areal extent are restricted to the Precambrian. Geologic processes operative since the Precambrian have effectively separated iron and silica and have resulted in extensive deposits of chert (Caballos novaculite, etc.) and of carbonate iron ores (Birmingham, Alabama, East Texas, etc.).

Differences between Precambrian and younger iron formations are attributed to secular changes in the atmosphere. In Precambrian times weathering akin to laterization retained aluminum, titanium, and phosphorous in the regolith, but unlike recent laterization processes, the Precambrian processes also supplied iron along with silica, alkaline earths, and alkalies to the groundwaters.

A relative deficiency in oxygen in the Precambrian atmosphere promoted the solution and transportation of iron as the bicarbonate. Fe and Ca are present in the lithosphere in mole proportions of about 1:1. It is postulated that siderite and roughly equal amounts of calcite were deposited on a relatively stable shelf (miogeosyncline). The primary carbonates were replaced in varying degree by silica. Iron silicates and iron oxides were developed through diagenesis and low-grade metamorphism.

The graphitic slates commonly associated with Precambrian iron formations indicate that primitive life was abundant.

POTASH DEPOSITS IN THE CARLSBAD DISTRICT, SOUTHEASTERN NEW MEXICO

C. L. JONES

U. S. Geological Survey, Menlo Park, California

In the Carlsbad district, southeastern New Mexico, certain salt layers in the middle of the Salado formation (late Permian) contain potash deposits. The deposits lie near the western margin of the Permian salt basin at depths ranging from 340 to 2,650 feet below the surface. They underlie about 900 square miles, almost equally divided between the structurally low Delaware Basin in the south and the higher standing Northwestern Shelf in the north.

The rock salt of the Salado formation accounts for one-half of a 4,500 foot section of marine evaporites, and separates anhydrite of the Castile and Tansill formations (late Permian) from younger evaporites of the Rustler formation (late Permian). Overlying the evaporites are strata, of different thicknesses, of Late Triassic and Cenozoic age.

The potash deposits are stratigraphically controlled and formed by replacement of interlayered halite and argillaceous halite rocks by bittern salts comprising various chlorides and sulfates of potassium, magnesium, and sodium. These salts form discrete, superposed, manto-like deposits having sharp outlines against the unmineralized host rock. Bedding planes extend uninterrupted from halite rock into the "mantos," although thin laminations within individual layers were destroyed in the course of recrystallization accompanying deposition of the bittern salts. The laminations, however, appear within small isolated remnants and large islands of halite rock enclosed by the "mantos."

Structural relations and stratigraphic distribution provide evidence in support of an epigenetic origin for the deposits. Metasomatism by reaction of residual potassium- and magnesium-rich bitterns with pre-existing halite rock is favored.

EVIDENCE OF THE ORIGIN OF BLIND RIVER URANIUM DEPOSITS —A PROGRESS REPORT

DUNCAN R. DERRY

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The paper, a coordination of data rather than original research, was first prepared for the November, 1958, meeting but was withdrawn due to the absence of the author. It is now revised to include later evidence from studies of the area, and of the ten mines now in full production, from sources including Government reports, studies by mine geologists and research for post-graduate degrees.

The main facts established are:

(1) Commercial ore is mainly restricted to certain quartz pebble conglomerate beds included in predominantly quartzitic Lower Huronian sediments and there is a direct relationship between maximum conglomerate development and grade of uranium.

(2) The source of the detrital material was from the basement rocks to the northwest.

(3) The ore minerals are uraninite and brannerite in a variable proportion, and in forms unlikely to be preserved as detrital grains.

(4) Age determinations show that definite detrital minerals have an age corresponding to that of the Archaen basement, while the uranium minerals have an age close to that of the deposition of the Lower Huronian sediments.

It is concluded that:

(a) The quartz-pebble conglomerates were deposited at least 1700 m.y. ago in estuaries of rivers carrying material from an older land mass to the northwest.

(b) Uranium minerals in their present form were deposited contemporaneously with, or shortly after, deposition of the beds not as detrital material but by precipitation from supergene solutions.

(c) Hydrothermal action does not appear to have played a more significant part than minor redistribution of the uranium especially in the vicinity of diabase dikes.

BASAL CHINLE SILICIFICATION

A. M. ABDEL-GAWAD AND PAUL F. KERR

Department of Geology, Columbia University, New York 27, New York

The base of the Chinle formation on the Colorado Plateau exhibits the activity of silica-bearing solutions. Local silification may be observed in a number of places associated with argillic alteration, bleaching, dolomitization, and uranium mineralization.

In the San Rafael Swell chert occurs as thin layers, veins and solid masses infiltrating siltstones, mudstones and sandstones. A green-gray bleached halo borders the chert and is characterized by the removal of iron. Silica deposition took place in at least two surges. In each fibrous and spherulitic quartz was deposited followed by cryptocrystalline quartz and finally druzy crystals formed. The final surge was associated with sulphide and uranium mineralization. Pyrite, marcasite, chalcopyrite, bornite, sphalerite, uraninite, covellite, calcite, dolomite, barite, and coffinite-bearing asphaltite are associated with the silica. Incipient

silicification is noted in the dolomitized zones where euhedral prismatic quartz crystals replace the carbonates.

Near Cameron, Arizona, jasper layers occur in a zone characterized by intense bleaching and silicification of the Basal Chinle-Shinarump contact.

Silicified "pipes" and quartz masses occur in mottled and bleached Basal Chinle outcrops at a point 11 miles east of Moab, Utah.

Silicification is attributed to hydrothermal activity. Hydrothermal solutions carrying silica in amounts above the equilibrium concentration deposited slica in colloidal form. The well crystallized quartz was deposited from the resultant less concentrated solutions.

RELATION OF THE TODILTO LIMESTONE URANIUM DEPOSITS TO COLORADO PLATEAU URANIUM DEPOSITS IN SANDSTONE

ALFRED H. TRUESDELL * AND ALICE D. WEEKS

U. S. Geological Survey, Washington 25, D. C.

The uranium deposits in the Todilto limestone near Grants, N. Mex., because different lithologically, have also been considered different genetically from the uranium deposits in sandstone of the Colorado Plateau.

Characteristics of the deposits in sandstone are: 1) The chemistry and mineralogy are simple. Uranium is usually associated with vanadium and few other elements are present. The primary ore contains uraninite, vanadium oxides, and coffinite and oxidizes chiefly to uranyl vanadates. 2) Deposition was epigenetic from circulating waters, controlled by primary sedimentary structures and organic matter, and usually limited to a single formation over a wide area. 3) Their consistent association with tuffaceous (or arkosic) sediments suggests a mechanism of formation involving leaching of uranium from the tuff (or arkose) by carbonate ground water with formation of uranyl tricarbonate complex which then moves to a different chemical environment where the uranium precipitates.

Deposits in the Todilto, like the sandstone ores, have uraninite, coffinite, and the vanadium oxides haggite and paramontroseite, which oxidize to uranyl vanadates and silicates. They occur over a large area in the Todilto within intraformational structures. They are associated with organic matter which both is intimately incorporated into the limestone to give a fetid odor and occurs as minute black glassy masses. The acid insoluble fraction, between 4 and 45 percent of the unmineralized limestone, contains arkosic and possibly tuffaceous material. Thus uranium deposits in the Todilto limestone are considered basically similar to the Colorado Plateau sandstone uranium deposits in mineralogy, occurrence, and origin.

URANIUM AND PHOSPHATE IN THE GREEN RIVER FORMATION OF WYOMING

J. D. LOVE AND CHARLES MILTON

U. S. Geological Survey, Laramie, Wyoming, and Washington, D. C.

Notably high concentrations of syngenetic uranium and phosphorus characterize at least three beds in the lower 100 feet of the partially lacustrine Wilkins Peak

* Indicates speaker.

member of the Green River formation (Eocene) in southwestern Wyoming. Uranium varies with phosphorus; uranium replaces calcium ions in carbonate fluorapatite.

The stratigraphically lowest, thickest (as much as 3 feet), richest, and most widespread zone, a dense gray "marlstone," has been identified along an outcrop distance of more than 100 miles. The richest 3 to 6 inches along 40 outcrop miles (16 sections studied) averages 0.060% eU, 0.055% U, 8.1% P_2O_5; maximum 0.15% U, 18.2% P_2O_5. Sixty feet higher one foot of a green blocky "claystone" along 16 outcrop miles (5 sections studied) averages 0.012% eU, 0.009% U, 3.4% P_2O_5; maximum 0.12%, 4.8 P_2O_5. Forty feet higher a 3-inch brown "oil shale" along 18 outcrop miles (5 sections studied) averages 0.013% eU, 0.012% U, 8.1% P_2O_5; maximum 0.019% U, 12.9% P_2O_5.

Chemical and X-ray study of one apparently typical "marlstone" shows 1/3 apatite, 1/8 dolomite, 1/4 zeolite (analcite?), and the remainder insoluble (detrital?) minerals.

Only a small part, stratigraphically and areally, of the Green River formation has been investigated. Probably many other beds with abnormally high concentrations of U-P_2O_5 exist, in Utah and Colorado, as well as Wyoming. Possible sources of U and P_2O_5 are volcanic ash in the Green River formation, and phosphatic Permian rocks eroded from the rising Uinta Mountains during middle Eocene time.

HOST ROCK AS A SOURCE OF IRON, AUSABLE FORKS MAGNETITE DISTRICT, N. Y.

A. F. HAGNER AND L. G. COLLINS

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Replacement magnetite deposits in Precambrian gneisses and skarn near Ausable Forks, New York formed by regional metamorphism and metasomatism. Material from the host rock moved to strongly disturbed, low-pressure zones and was localized by structural features. Eight square miles were mapped on a scale of 1 inch to 880 feet, and two deposits on a scale of an inch to 200 feet. Geologic interpretations are based on field studies, 320 analyses, over 500 refractive index determinations, 22 fluorescent X-ray analyses, and 10 spectrographic analyses of minerals and rocks.

Magnetite in the gneiss drops from 4 percent at distances greater than 500 feet on either side of the ore zones to 0 percent adjacent to them. The percent mafic minerals also decreases near the ore zones. More than enough magnetite has been removed from the gneiss to account for the ore bodies. Ore formed by removal of primary accessory magnetite, release of iron from mafic silicates and substitution by magnesium without breakdown of these minerals, and by release of iron during alteration and breakdown.

Around the small, scattered magnetite bodies in clinopyroxene skarn, there is no gradual decrease in percent accessory magnetite or of mafic silicates, and clinopyroxene does not break down to alteration products with release of iron. Clinoproxene also shows no decrease in iron percent; it is, however, lower in iron than that outside the mapped area. Magnetite in the skarn deposits formed by recrystallization of iron-rich clinopyroxene and hornblende to clinopyroxene relatively poor in iron.

PHASE STUDIES IN THE FE-RICH CARBONATES OF THE BUNKER HILL MINE, IDAHO

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The Bunker Hill mine lies within the Coeur d'Alene district of northern Idaho. Both the mine and the district are well-known for the association of iron carbonate minerals with sulfide orebodies of lead, silver, and zinc. Host rocks of the mine are Revett quartzites and St. Regis argillites of the pre-Cambrian Belt series. The carbonate minerals—siderite, ankerite, and calcite—occur singly or in the pairs siderite-ankerite and ankerite-calcite. Compositions, determined from one hundred chemical analyses of gangue and wall rock carbonates, are:

siderite, $(Fe_{.75-.85}Mn_{.08-.10}Mg_{.05-.10}Ca_{.02-.06})CO_3$

ankerite, $Ca_{1.00-1.12}(Fe_{.50-.70}Mg_{.20-.30}Mn_{.06-.12})(CO_3)_2$

calcite, $(Ca_{.96-.97}Fe_{.016-.024}Mn_{.008-.015}Mg_{.004-.006})CO_3$

The distribution of the carbonates was determined for 350 samples, including samples from ore-bearing structures and wall rock. Siderite is most abundant in and near ore-bearing structures; ankerite away from these structures; and calcite no closer than 200 feet from ore-bearing structures. It is proposed that this distribution resulted from hydrothermal differentiation during mineralization. Consideration of aqueous carbonate systems, on the basis of general principles of heterogeneous equilibria, suggests the possibility of zoning of the carbonate minerals in veins and wall rock, with respect to a point of initial precipitation in the vein system, in the order: (1) siderite, (2) siderite + ankerite, (3) ankerite, (4) ankerite + calcite, and (5) calcite. This pattern is observed in some sections of wall rock in the mine. The two most calcic zones, however, are not represented in ore-bearing structures.

SOLID DIFFUSION AND VOLATILITY OF SULPHIDES—SOME EXPERIMENTAL RESULTS

J. E. GILL

Experiments carried out by J. F. MacDougall, B. K. Meikle, and J. V. Guy Bray under the direction of J. E. Gill and V. A. Saull, prove that some sulphides generally regarded as non-volatile are slightly volatile under low sulphur vapor pressures. Chalcocite heated in nitrogen and sulphur vapor showed appreciable volatile transfer at 675° C in the presence of excess sulphur. Pyrite in a similar environment was transferred at 550° C. In experiments with no excess sulphur no transfer occurred.

Some volatile transfer of cobalt sulphide was effected. Other sulphides tested gave no positive evidence of volatilization.

Solid diffusion was evident in many experiments and this, rather than volatilization, is thought to have been the main process producing crystals on the surface of test specimens, veinlets of sulphides along fractures in mineral grains and rock fragments, and replacement of one sulphide by another. Textures produced re-

semble some in natural ores commonly attributed to replacement through the agency of aqueous solutions.

Silicates and carbonates heated in a nitrogen atmosphere with copper sulphides at 550° C and 825° C gave no evidence of replacement, though some may have occurred in chlorite.

THE ECONOMIC SIGNIFICANCE OF THE BIOGEOCHEMISTRY OF CARBONATE APATITES

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The economically important sedimentary (including low-temperature metasomatic) rock phosphates are composed of carbonate-apatite minerals. Carbonate apatites are also of primary concern in connection with medical and dental research because of their occurrence as the inorganic constituent of bones and teeth.

Substitutions that can occur in the crystal structure of fluorapatite to produce isomorphic variants are diverse and may be related to such byproduct recoveries as uranium and vanadium. Assimilations of strontium-90 and fluorine are related to public health.

Correlation of knowledge on the physiological chemistry of bones with geochemical knowledge indicates that formation of carbonate apatites is a complex reaction which probably cannot take place independently of organisms or their products. Consideration of Ca to P ratios of bone and of mineral carbonate apatites leads to the hypothesis that bone has an unstable precursor, which forms carbonate apatite through hydrolysis and carbonation. The analogy between precipitation of the bone "mineral" and phosphorites may be very close indeed.

SPHALERITE TEMPERATURES FROM THE BRUNSWICK AND NIGADOO DEPOSITS, NEW BRUNSWICK, CANADA

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The Brunswick lead-zinc-copper deposit is a large, lenticular, massive, fine-grained replacement, consisting essentially of pyrite with galena and sphalerite. Along the foot-wall an adjoining zone contains pyrrhotite, chalcopyrite and little sphalerite and galena. Twenty-five sphalerites from this deposit were analyzed for iron by x-ray fluorescence techniques. Where pyrite is the chief iron sulphide the iron content in the sphalerite ranges unsystematically from 8.5% to 12% FeS (295° to 400° C). In the part containing pyrrhotite the iron content is consistently higher, near 13.5% FeS (430° C). This relationship is in complete accordance with theory.

The Nigadoo deposit is a coarse-grained xenothermal vein. In an unpublished paper Aleva describes a deeper zone of pyrrhotite grading upward into marcasite and pyrite. The most abundant of the associated minerals are calcite, sphalerite, galena, chalcopyrite, arsenopyrite, lollingite, and stannite. Fifteen sphalerites from various associations show a 3.5% spread of FeS content, in the range considered tentatively to be from 20% to 23.5% FeS (580 to 650° C). Nine of the sphalerites

show a content of about 0.5% Mn and from 0.6 to 0.9% Cd. The reason for the variation in iron content is obscure.

The above deposits are geologically similar respectively to Heath Steele and to Sturgeon River. Sphalerite from the former gives values near 325° C and for the latter near 590° C.

TRACE ELEMENTS IN SULFIDE MINERALS FROM THE CENTRAL DISTRICT, NEW MEXICO, AND THE BINGHAM DISTRICT, UTAH

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A total of 373 samples of chalcopyrite and sphalerite from the Central district, New Mexico, and the Bingham district, Utah have been analyzed spectrographically for trace element content. Chalcopyrite and sphalerite from both districts can be divided into two or more groups of differing trace element content and location within the districts. Geologic and mineralogic differences exist between the ores of different groups in some cases, but enough similarities of host rocks and mineral associations exist to conclude that temperature and other conditions at the time and site of deposition are not the principal cause of the grouping, but that differences of trace element content probably existed in the ore fluids before they reached the site of deposition.

Within the main sphalerite group in the Central district, a poorly developed lateral zoning away from the Hanover-Fierro and Santa Rita instrusives exists. Iron, manganese and cobalt in the sphalerite decrease away from the intrusives, and gallium increases. The lead-zinc ratio and the silver content of the ores show similar zoning. Less definite zoning is found in chalcopyrite from the Central district and sphalerite from Bingham. Either temperature gradients or progressive concurrent changes in the composition of the ore fluid and the site of deposition are possible causes of the zoning.

The above effects account for only part of the trace element variability within the districts. Local poorly understood variations in the mineralizing process are apparently responsible for much of the variability found.

FLUID INCLUSIONS AS SAMPLES OF THE ORE-FORMING FLUIDS

EDWIN ROEDDER

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Data from studies of fluid inclusions in transparent ore and gangue minerals, such as quartz, calcite, fluorite, and sphalerite, from hydrothermal ore deposits have been examined critically for evidence regarding the heavy (ore) metal content of the ore-forming fluid. The following conclusions are reached:

1. At least *some* inclusions in ore and gangue minerals, at the time of trapping, contained the identical fluid from which the ore and host minerals were precipitating, and which was saturated with respect to these minerals.

2. These inclusions, in most cases, have not lost or gained appreciable quantities of material since being trapped.

3. Simple calculations show that *if* decreasing temperature was a significant

factor in causing precipitation of the ore minerals in the deposit, these should also precipitate from the fluid in the inclusions, upon cooling.

4. Such precipitated mineral grains are very rarely seen, even in the larger inclusions.

5. Although there are alternative explanations, the quantitative evidence supports the concept of the ore-forming fluids being exceedingly dilute in the ore metals—in the range of 0.001–0.01 gram per liter up to a maximum of perhaps 0.1 gram per liter.

6. In spite of the low concentrations, these dilute solutions are still geologically reasonable.

SULPHUR ISOTOPE INVESTIGATION OF THE GOLD-QUARTZ DEPOSITS OF THE YELLOWKNIFE REGION [1]

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Sulphides in the orebodies and their associated alteration halos, the metamorphic facies of the greenstone belt, and the neighboring granite have been examined in detail. Most samples investigated are slightly enriched in S^{34} with respect to the meteoritic standard. While the overall range is small (abouput 1.5%), variations were found between the granite and the metamorphic facies of the greenstone belt. A direct correlation exists between the isotopic ratio and the distance from the granite contact; sulphides in the granite are the most enriched in S^{34} whereas the metamorphic facies are progressively depleted in S^{34} as the distance from the granite increases.

Sulphides in early tension fractures are consistently lighter (i.e. contain more S^{32}) than the sulphides in the surrounding greenstones, while sulphides in the later gold-quartz lenses are heavier than those in their associated alteration zones. In addition, profiles across the country rock, alteration zones, and gold-quartz lenses indicate that the heavy isotope has been preferentially retained in the alteration zones with the maximum enrichment in the ore. However, in late cross-cutting quartz-carbonate lenses the lighter sulphur isotope has been preferentially concentrated.

The isotopic studies indicate that the primary isotopic distribution of the district was modified by metamorphism during which the S^{32} was mobilized to a greater extent leaving the sulphides in the hotter regions enriched in S^{34}. The formation of the gold-quartz lenses was associated with intense chemical activity and the S^{32} was again preferentially mobilized, resulting in a progressive enrichment of S^{34} in the alteration zones and ore.

SULFUR ISOTOPES AND THE ORIGIN OF THE HEATH STEELE ORE DEPOSITS, NEW BRUNSWICK, CANADA

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Middle Ordovician Tetagouche Group rocks in the Heath Steele mines, New Brunswick, Canada area, form a steeply plunging recumbent anticline. The ore

[1] Published by permission of Director Geological Survey of Canada, Ottawa.

deposits of Zn, Cu, and Pb are associated with minor folding and/or sheared dilatant zones at or near the contact between sericitic schist and quartz feldspar porphyry.

Sulfur isotopic ratios have been determined at Yale University for more than 500 sulfide and sulfate specimens from New Brunswick. Some 150 analyses are of samples from the several mines of the Heath Steele property (and adjacent country rock) for which primary and secondary (supergene) ore sulfides exhibit similar values that average about 21.9 in S^{32}/S^{34} ratio ($\delta S^{34}\% = +14.0$). The enrichment of S^{34} in the ore sulfides and the presence of graphite, evident from mineralographic studies and mass spectrometric analyses, suggests reduction of original sulfates at temperatures in excess of 500–600° C during the creation of a magma from which it is inferred the ore solutions were derived.

Magmatic hydrothermal solutions presumably become concentrated and thereby homogenized in the latest crystallizing phase of intrusive bodies, whereas metamorphic hydrothermal solutions derived from heterogeneous sources may never have a chance of extensive intermingling before mineral deposition occurs. S^{32}/S^{34} analyses of non-ore sulfides collected from country rock throughout northern New Brunswick vary between 21.9 to 22.7 and average about 22.3 in ratio. In comparison, the average of sulfide ore samples is about 21.9 and for the Heath Steele mines varies only between 21.82 to 22.02, which is suggestive of a well homogenized, magmatic hydrothermal source of ore (sulfur) solutions.

S^{32}/S^{34} ISOTOPIC ABUNDANCE RATIOS AND GENESIS OF SULFIDE ORE BODIES AT SUMMITVILLE AND ELLENVILLE, NEW YORK [1]

JULES D. FRIEDMAN

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Laboratory and field investigation of the sulfide ore body at Summitville and of remaining accessible exposures of the ore body at Ellenville, New York, reveal basic similarities in the chief minerals present, paragenesis, and structural control, although differences in auxiliary minerals and zoning were noted. Sphalerite geothermometry indicates that the upper part of the Summitville ore body formed at approximately $325 \pm 25°$ C; pressure was not greater than 10,000 atmospheres. Ore-forming fluids rich in zinc, iron, lead, and copper and carrying traces of gold, silver, cadmium, and manganese were deposited at the Summitville locality during a single period of sulfide metallization, preceded and accompanied by tectonic activity; they are interpreted as mesothermal hypogene deposits.

Supergene sulfide deposition and development of an oxidized zone at Summitville did not advance beyond an initial stage. Uniformly low S^{32}/S^{34} abundance ratios between 21.72 and 21.74, a comparatively narrow spread $< \pm .02$ percent, are below those previously reported for sulfides of undoubted biogenic and sedimentary origin; the narrow range may support geothermometric evidence for a hypogene origin of the ore body. S^{32}/S^{34} ratios may distinguish exsolved chalcopyrite and sphalerite (21.72) here from a later replacement generation of chalcopyrite (21.66), and vein pyrite (21.55) from other pyrite (21.70).

[1] Publication authorized by the Director, U. S. Geological Survey.

AN ELECTROCHEMICAL STUDY OF OXIDATION OF SULFIDE MINERALS AT 25° C

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Measurements of the single electrode potentials of sulfide minerals backed with a basic understanding of their electrode behavior make it possible to clarify their oxidation or reduction mechanisms. The electrode potential of a sulfide mineral is controlled by the first-step reaction of the oxidation mechanism for the sulfide in an oxidizing solution, and by that of the reduction mechanism in a reducing solution. Sulfides of copper, lead, silver, iron, and zinc were studied. The results indicate that the direct oxidation of a simple sulfide mineral is a process in which the metal atoms move into the surrounding solution to become aqueous cations, accompanied by a step-wise decrease in the metal to sulfur ratio of the remaining solid phase. When solid sulfur is finally left over, it undergoes a series of reactions to be oxidized to sulfate ion. In case of reduction, sulfur atoms move out into the solution to become aqueous sulfide ions with a step-wise increase in the metal to sulfur ratio of the solid phase. To illustrate, the oxidation of chalcocite proceeds as:

$$(Cu_2S) \rightarrow \tfrac{1}{8}\,(Cu_9S_5 + C^{++})\,? \rightarrow (CuS + Cu^{++}) \rightarrow (S + 2Cu^{++})$$

The path of the step-wise oxidation is not necessarily the same as that of the step-wise reduction for a metal-sulfur system. In the case of disulfides of iron, namely pyrite and marcasite, ferrous ions and S_2 molecules appear to be released into the solution simultaneously upon oxidation.

TIME CRITERIA IN ORE GENESIS: A REVISION

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Observations of past geological processes render usually only data of space (S) and composition (C). Time (T) concepts require interpretations based on geometric (Δs) and geochemical differences (Δc). Time differences (Δt) are thus "frozen into the rock" as Δs, Δc, and $\Delta c/\Delta s$ values. The expressions $\Delta s/\Delta t$, $\Delta c/\Delta t$, and $\delta^2 c/\delta s \delta t$ are thus normally interpretations and may be zero or near zero (syngenetic formations) or of a certain value (epigenetic formations).

With this in mind, a revision leads to the following suggestions: 1. Certain criteria currently used include assumptions of $\Delta c/\Delta t$ and $\Delta s/\Delta t$ which are not justified. 2. It is probably not possible to avoid a basic revision of the present genetic terminology. It was required a) a liberation of certain terms such as zoning, hydrothermal, replacement, etc. from the epigenetic meaning obtained during a period which favored an epigenetic introduction of material as the main ore-forming process; and b) the introduction of some purely descriptive, international classification of rock textures and mineral intergrowths. 3. A syngenetic interpretation requires usually less than half the number of assumptions required for an epigenetic theory. 4. Sedimentary petrology is at least as important in ore genesis as igneous petrology. 5. An integration of old and new geometric and geochemical evidences may lead to the following classification of mineral deposits: Except for transitional types, most deposits in sediments are of sedimentary and most deposits

in igneous rocks of igneous origin. Syngenetic and consanguineous formation is the rule, epigenetic metasomatism the exception which is practically always restricted to marginal crosscutting zones and veins.

TRACE FERRIDES IN IRON ORES FROM THE IRON SPRINGS DISTRICT, UTAH

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Investigation of the trace ferrides cobalt, manganese, nickel, titanium, and vanadium was made on samples of ore collected from accessible iron deposits associated with three monzonite porphyry intrusions in the Iron Springs District, Utah.

Iron mineral grains were separated and spectrochemically analyzed on a 1.5 meter, 24,400 lines per inch grating, Abney mount spectrograph. Iron was the variable internal standard.

Polished sections of separated iron grains of all samples collected were studied and mineral relationships and the percentages of magnetite, hematite, limonite, and sulphides were determined.

Quantitative data obtained were subjected to statistical analyses. The results of the analyses revealed several specific relationships:

1. The trace ferrides are of the same primary genetic population, based on similar abundances of cobalt, titanium, and vanadium.
2. The degree of oxidation of the iron ores in the Iron Mountain area is significantly different from that of the iron ores in the Granite Mountain-Desert and Three Peaks areas.
3. Manganese and nickel from the iron ores of the Granite Mountain-Desert, and Three Peaks areas belong to one statistical population, whereas that of the Iron Mountain area belongs to another statistical population. This relationship and the state of oxidation of the iron ores are apparently related. In the more oxidized areas, nickel has been enriched and manganese has been impoverished.

JASPEROID AND ORE DEPOSITS IN THE TINTIC AND EAST TINTIC MINING DISTRICTS, UTAH

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This investigation was conducted to determine the relationships of jasperoid masses to orebodies in the Tintic and East Tintic mining districts of Utah. Samples were collected from surface exposures, diamond drill cores and several mines.

Minerals and textures were determined petrographically in 118 thin sections. In addition, semiquantitative spectrographic analyses were obtained for 37 elements in 55 of the samples and for 10 elements in 63 of the samples. The data obtained were studied to determine differences between jasperoids associated with known ore deposits (productive jasperoid) and jasperoid masses isolated from ore deposits (barren jasperoid). Both the petrographic and spectrographic studies indicated that differences exist between the two types of occurrences.

* Indicates speaker.

Petrographic work has shown that textural features such as relict microbrecciation, vugginess and variable silica grain size are more common in productive jasperoids. The presence of sulfides, barite, sericite, clays and hematite pseudomorphs after pyrite is indicative of proximity to ore. Barren jasperoids tend to be less porous than productive ones and are characterized by the presence of fibrous chalcedony and iron oxide staining.

Spectrographic data indicate that antimony, bismuth, cadmium, copper, lead, silver, sodium, tantalum and zinc are more abundant in productive jasperoids, and that calcium and magnesium are more common in barren jasperoids.

There are exceptions to these generalizations, but a statistical treatment of the data shows a significant variation between barren and productive jasperoids.

MEASUREMENT OF PORE SIZE DISTRIBUTION IN SOME HYDROTHERMALLY ALTERED WALL ROCKS

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Pore sizes and their distribution were determined for a series of altered andesites sampled perpendicular to a leptothermal Pb-Zn-Ag vein in the Topia Mining District, Durango, Mexico. The alteration zone paralleling the vein consists of a wide propylitized band and a narrower superimposed quartz-sericite band adjacent to the vein.

The data were obtained by use of a mercury capillary apparatus. The pore entry size is determined by measuring the pressure applied to a non-wetting fluid (mercury) to bring it in equilibrium with the capillary pressure of the pore being investigated. By measuring the volume of mercury injected at given increments of pressure ranging from 0 to 2,000 psi, the pore entry size range and the portion of the void volume they occupy are determined.

Pore size distribution curves show that in fresh and altered andesites the greatest number of pores have a pore entry radius of .1 micron or less. With increasing alteration intensity, greater numbers of very small pores are created. As the vein is approached there is a corresponding increase in the number of pores .1 micron and smaller in radius. Larger pores also form but they are relatively few in number. The study demonstrates that the alteration process creates an environment characterized by a large amount of surface area available as potentional reaction sites.

SILICA-CEMENTED SANDSTONES AS A GUIDE TO UNOXIDIZED URANIUM DEPOSITS IN THE SOUTHERN BLACK HILLS, SOUTH DAKOTA

EDWIN V. POST

U. S. Geological Survey, Denver, Colorado

Spatial relations between silica-cemented sandstone and unoxidized uranium deposits in the southern Black Hills suggest that such silica-cemented sandstone may represent a broad alteration halo both stratigraphically above and laterally adjacent to areas of primary uranium deposits. Highly corroded quartz grains in

specimens of carbonate-rich uraninite-coffinite ore suggest that silica was leached during the process of mineralization. The silica not used in the formation of coffinite migrated in ground water until precipitated to form the silica-cemented sandstone.

A cursory review of the chemistry of silica, uranium, and calcium carbonate suggests the following process: Uranium traveled as a carbonate complex in carbonate-rich waters in channel sandstones. Where geologic conditions allowed the release of CO_2 or the addition of reducing solutions, calcite precipitated, followed by uranium minerals. Such conditions seem to be present where pinching out of an impervious mudstone unit has resulted in contact between a channel standstone and an overlying channel sandstone. Silica was released during the replacement of quartz by calcite and migrated in ground water solutions that were concentrated perhaps up to the saturation point for quartz. Subsequent precipitation of silica as quartz overgrowths and chalcedonic cement may have been caused by a reduction in the temperature of the ground water, or alternatively by equilibration of dissolved silica with quartz in stagnated water trapped in structural highs.

Silica-cemented sandstone may, therefore, be a valuable guide to ore during exploration for "blind" uranium deposits in the southern Black Hills.

GROUND WATER FROM SPRINGS IN CALHOUN COUNTY, ALABAMA [1]

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A study of 146 springs in Calhoun County was made during 1956–59 as a part of the ground-water investigation by the U. S. Geological Survey in cooperation with the Calhoun County Board of Commissioners and the Geological Survey of Alabama. The purpose of this investigation is to relate the geology of Calhoun County to the occurrence, quantity, quality, and availability of ground water.

The stratigraphy and structural relationships of the rocks in the area are typical of the Ridge and Valley physiographic province. Consolidated rocks ranging in age from Precambrian to Pennsylvanian have been sharply folded into northeastward-trending synclines and anticlines complicated by thrust faults. These thrust faults are the predominant structural feature of the area.

In comparison with springs studied in other parts of the Paleozoic area of northern Alabama, those in Calhoun County have smaller seasonal fluctuations in discharge. A detailed study of the discharges from 10 selected springs was made to determine seasonal fluctuations. Average flows from springs originating along fault zones ranged from 1.4 to 2.3 times the minimum flow; those from aquifers recharged locally were 3.4 to 6.3 times the minimum flow. The total minimum discharge from springs in the county exceeds 90 million gallons per day.

The fluoride content of water from 14 springs sampled ranged from 0.1 to 0.2 part per million, whereas only 1 of 11 water samples collected from selected wells contained a measurable quantity of fluoride.

[1] Publication authorized by the Director of the U. S. Geological Survey.
[2] Geologists, U. S. Geological Survey.

JOINTING WITH RELATION TO GROUND WATER MOVEMENT IN THE TRIASSIC ROCKS OF NEW JERSEY

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The New Jersey Geological Survey is successfully utilizing the topographic expression of joint systems as a means of locating wells in Triassic sandstones and shales.

A statistical tabulation of well depths and yields in an area is checked against the structure, rock type, and joint systems. Such tabulations are providing clues as to the minor changes in rock types, the abundance of argillite, and structure in the areas studied.

A number of case histories and examples are given to show that: (1) there is relatively free and rapid movement of ground water through joints within about two-hundred feet of the surface; (2) at depth there is more rapid ground water movement in zones of closely spaced joints; (3) not all joint systems are open enough for ground water movement; (4) the intersection of bedding planes and selected joint systems may provide better openings for ground water movement than joints alone; (5) at depth, ground water movement may be at a rate of a few feet per day, with a consequent drop in the well yield; and (6) rapid depletion of wells along a major joint at a distance of a half mile or more may occur while at the same time other wells within two hundred yards of the pumping well are unaffected.

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SCIENTIFIC NOTES AND NEWS

EMMONS MEMORIAL FELLOWSHIP

The S. F. Emmons Memorial Fellowship in Economic Geology is available for the academic year 1960–61, with a stipend of $1,600.00. Applications and accompanying testimonials should be submitted not later than February 15, 1960.

Applicants should be qualified by training and experience to investigate some problems in Economic Geology and should submit a definite statement of the problems to the Committee, under whose supervision the work may be undertaken at any institute approved by them. The Fellow must give entire time to the problem, which may be used for a doctoral dissertation. Application blanks may be obtained from Alan M. Bateman, Yale University, Charles H. Behre, Columbia University, H. E. McKinstry, Harvard University, or the Secretary, Columbia University.

JOHN S. BROWN, Chief Geologist, St. Joseph Lead Company, Bonne Terre, Missouri, retired October 1st, after 34 years of service. He is succeeded by FRANK G. SNYDER.

LOUIS L. RAY, on leave from the U. S. Geological Survey during the academic year 1959–60, is serving as Visiting Professor of Geology at Cornell University, Ithaca, New York.

SIEGFRIED MUESSIG has resigned from the U. S. Geological Survey and is now chief geologist of United States Borax & Chemical Corp. at Los Angeles, California.

DAVID WILLIAMS has been elected President of the Institution of Mining and Metallurgy, London, in succession to Dr. J. H. WATSON. He will take office in May, 1960.

THE III VENEZUELAN GEOLOGICAL CONGRESS will be held at Caracas, Venezuela, Nov. 22 to Nov. 29, 1959, to consider matters inherent to geology in the scientific, technological and economic, as well as educational fields. The Congress is of a national character, but the organizing committee has invited representation from some neighboring countries. The subjects to be considered consist of General Geology, Applied Geology, Stratigraphy, Petrogeny, Tectonism and Sedimentation, and Field Trips.

The University of Cincinnati announces the formation, on September 1, 1959, of two new departments: the Department of Geology, headed by Dr. William F. Jenks, and the Department of Geography, with Dr. Peter H. Nash as Head. These two departments were formerly joined in the Department of Geology and Geography. The University has completed the preparation of space for new laboratories for research in geochemistry, crystallography, crystal chemistry, hydrothermal geology, and sedimentology.

ROBERT MACKAY of Mackay & Schnellmann, Geological Mining Consultants of London, has been visiting Canada and the United States.

CHESTER M. F. PETERS has returned to New York from Saudi Arabia after completing a five-month assignment locating and drilling quarries for raw materials for the Damman Pier project.

WARREN H. WESTPHAL, former chief geophysicist for the Utah Construction Company, has joined the staff of Stanford Research Institute's Earth Sciences Department as senior geophysicist to undertake Institute projects in mining and geophysical exploration.

The University of Toronto announces the following recent appointments in the Department of Geology: Dr. TIBOR ZOLTAI, Assistant Professor in mineralogy and crystallography, and Dr. WILLIAM C. PHINNEY, Assistant Professor in petrography and petrology.

RAYMOND C. MOORE, principal geologist of the State Geological Survey of Kansas and Professor at the University of Kansas, was elected honorary member of the Kansas Geological Society in October.

A. F. BANFIELD, geologist of Behre Dolbear & Company, consultants, New York, is in Jutland cooperating with Danish Government officials in the study of extensive salt deposit.

SAMUEL H. DOLBEAR, President, and PARKE A. HODGES, Vice President of Behre Dolbear & Company, are engaged in mine valuation in California.

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